Assessing nonlinearities in the price discovery process of Brazilian cross-listed stocks on NYSE and B3

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Abstract

This paper examines price discovery process for Brazilian companies cross-listed on the New York Stock Exchange (NYSE) and the São Paulo Stock Exchange (B3) through a threshold error correction model to incorporate nonlinearities on the price parity dynamics. Based on the market-respective component shares, the relative contribution of each market to the price discovery of cross-listings is computed for the inner and outer regimes. The empirical findings indicated that prices at NYSE and B3 have showed a threshold effect on the convergence dynamics (long-run equilibrium). As the required arbitrage return widens beyond a threshold (outer regime), caused by market imperfections, arbitrage operations take place and influence price dynamics distinctly. More than 30% of the data falls, on average, in the outer regime, indicating the evidence of arbitrage opportunities for cross-border traders as the cross-listing dollar premiums sufficiently diverge from parity. Finally, the local exchange, B3, plays a more informative role to parity convergences, which is even higher in the outer regime. However, the NYSE still makes a significance contribution to price discovery.

Keywords: price discovery, arbitrage, threshold error correction models, cross-listed stocks, Brazilian ADRs.

JEL codes: C32, G14, C58.

1 Introduction

The study on how new information is incorporated into asset prices concerns the idea of price discovery, which is a central function of a market in addition to liquidity, as stated by O'Hara (2003). Price discovery plays a particular role when related to cross-listings, when a same asset is negotiated in multiple markets, as informations can be incorporated into asset prices by each market differently. In such case, the analysis of price parity also provides relative information efficiency and reveals investors trading preferences for each market (FRIJINS; GILBERT; TOURANI-RAD, 2015). Therefore, the discussion on where and how price discovery occurs, i.e. how information is priced in different markets, is of great importance.

Due to the increasing globalization and technology advances in financial markets, international cross-listing activities have showed a considerable growth, being the analysis of prices behavior worth examining. Particularly, many foreign firms issued American Depositary Receipts (ADRs) as an alternative to raise capital from American investors through United States (US) exchanges, which also provides US investors with an opportunity to trade in shares of a foreign company[1]. According to the law of one price to financial assets, foreign and US stock prices should be identical across markets, as ADRs can be exchanged for the underlying foreign stocks and vice versa. However, the existence of market frictions, microstructure noise, legal barriers and unsynchronized trading led to price deviations across markets creating arbitrage

[1] In 2020, the New York Stock Exchange (NYSE) showed an average daily volume of USD 123 billion related to international listings trading (ADRs). Source: <https://www.nyse.com/listings/international-listings>. Access on 24 June, 2020.

opportunities in order to keep the price in each market from drifting away from the implicit efficient price, determined by the new informations (SU; CHONG, 2007; BAILLIE et al., 2002).

Empirical literature concerning cross-listed stocks generally indicates the predominance of price discovery in the home market, as it provides more information about the companies, e.g. new financing, dividends, and earnings announcements (FRIJINS; INDRIAWAN; TOURANI-RAD, 2018; GHADHAB; HELLARA, 2016; ALHAJ-YASEEN; LAM; BARKOULAS, 2014; FRIJINS; GILBERT; TOURANI-RAD, 2010; BACIDORE; SOFIANOS, 2002). However, in integrated markets, with reduced cross-border barriers, this argument neglects the possibility of investors in choosing the cheapest and most liquid trading venue. Further, literature have also achieved that significant information flows from the US stock exchanges to the foreign countries equity share markets, indicating that US exchanges play an important feedback in the price discovery process and thus its relevance on information processing capacity, i.e. its competitiveness in the intermarket arbitrage opportunities (FRIJINS; INDRIAWAN; TOURANI-RAD, 2018; GHADHAB; HELLARA, 2016; OTSUBO, 2010; PASCUAL; PASCUAL-FUSTER; CLIMENT, 2006).

The approach usually considered by the literature to evaluate the process of price discovery for cross-listing assets is the common factor method, proposed by Harris et al. (1995) and Harris, McInish and Wood (2002). The information share of each market is estimated according to a permanent-transitory decomposition of a cointegrated system, where the corresponding stock-ADR prices are cointegrated by the law of one price[2]. The cointegrating vector of the error correction term represents the associated near-parity condition, i.e. the long-run equilibrium dynamics, and the error correction adjustment coefficients characterize the convergence mechanism induced by market imperfections (HARRIS et al., 1995). Thus, the estimates of adjustment coefficients are used to compute the relative contribution of each market to the price discovery of cross-listings[3].

Price discovery framework of Harris et al. (1995) and Harris, McInish and Wood (2002) assumes that the long-run equilibrium (the adjustment to parity) is continuous and linear, which is not necessarily verified in the presence of transaction costs and policy interventions. Gagnon and Karolyi (2010) showed that market frictions such as taxes, transaction costs, holding costs and short-sale restrictions comprised observable sources for impediments to arbitrage parity. When related to cross-listing assets, transaction costs correspond to commissions to home and host exchanges, bid-ask spreads on the cross-listed pair and the foreign exchange rate, as well as price impacts on both cross-border listings (CHEN; CHOI; HONG, 2013). Additionally, cross-border differential adverse selection risks and agency walls between the entrusted arbitrageurs and their investor clients are also obstacles to price parity convergence (CHEN; CHOI, 2012; SHLEIFER; VISHNEY, 1997). Alsayed and Mcgroarty (2012) demonstrated that arbitrage opportunities exist between stocks and their ADRs through convergence pairs trading. Further, considering United Kingdom firms stock-ADRs prices, Mitra et al. (2019) recently showed that the corresponding arbitrage pair trading is directly influenced by the market microstructure of ADRs and, most importantly, found that pair trading returns exhibit substantial asymmetry in returns: pair trades involving ADR shorts (compared to stock shorts) have significantly less probability of loss, substantially higher returns but higher convergence risk.

Due to these market frictions, a proper methodology to capture parity-convergences of cross-listed pairs consists in the use of a nonlinear approach. Chen, Choi and Hong (2013) advocated that relatively small deviation of the price of a cross-listing from its parity-implied price is unarbitrageable if the dollar spread is insufficient to cover fees, commissions, liquidity shortfalls, and other related costs, thus, the dollar premium or discount behaves like a near-unit root process and will not converge to parity. As the spread widens beyond a threshold, determined by transaction costs and associated risk premiums, arbitrages operations take place and influence price dynamics. Hence, multiple and overlapping regime-switching effects are suitable to properly measure the transition from a profitable to an unarbitrageable status (CHEN; CHOI; HONG, 2013).

[2] The work of Narayan and Smyth (2015) reviews the econometric developments in the literature on price discovery.

[3] Another broad approach considered to evaluate price discovery of cross-listing stocks is the Hasbrouck (1995) information shares, which are obtained by variance decomposition of a vector moving average representation of an error correction model. However, as stated by Eun and Sabherwal (2003), this method yields multiple information shares values, due to the necessity of using the Cholesky factorization of the covariance matrix of innovations to prices, which may cause confusing results.

Rabinovitch, Silva and Susmel (2003), Chung, Ho and Wei (2005), Koumkwa and Susmel (2008), and Chen, Choi and Kim (2008) are examples that suggested the advantages of nonlinear frameworks for analysing the asset pricing aspect of cross-listings. In addition, Chen, Choi and Hong (2013) showed empirical evidence of nonlinearities on the price discovery process of Canadian firms cross-listings.

Hence, the aim of this paper is to propose the use of a threshold cointegration error correction model for the study of price discovery of Brazilian cross-listed stock pairs traded simultaneously on the New York Stock Exchange (NYSE) and the São Paulo Stock Exchange (B3). Based on a sample of 24 Brazilian firms cross-listed on the NYSE and B3 between 1997 and 2019, measures of price discovery are computed from adjustment coefficients of a two-regime threshold error correction model, allowing the discrete dynamics of abrupt parity-convergences, which are caused by risk factors such as information asymmetry and market frictions. Nonlinear tests are also examined to test the hypothesis of linear cointegration against threshold cointegration for the Brazilian cross-listing stocks. Relative exchange contributions to price parity dynamics, computed from the nonlinear approach, are also compared to a linear error correction model in order to assess the influence of nonlinearities on the price parity dynamics of Brazilian stock-ADR pairs.

The main contribution of this paper to the literature is to provide empirical evidence on the nonlinear behavior of price discovery related to cross-listing assets, which reflects the relative contributions of each market to price adjustments to a higher degree compared with existing linear approaches as well as circumvent the time- and regime-contingent characteristics of information shocks. Moreover, to the best of our knowledge, this work is the first to suggest a threshold error correction model to analyze the price discovery of Brazilian cross-listed companies, addressing nonlinearities from market imperfections in the corresponding parity convergence[4]. Besides the relevance and increasing trading volume of Brazilian firms equities quoted simultaneously on the NYSE and B3, which corroborate the importance of the present study, allowing for nonlinearities in the price discovery process plays a particular role, as emerging economies like Brazil are prone to market frictions and noise trading.

After this introduction, the paper proceeds as follows. Section 2 provides a literature review on price discovery of cross-listed stocks. The nonlinear threshold error correction model for price discovery of cross-listings are described in Section 3. The data, statistical tests, estimation results and the corresponding discussions comprise Section 4. Finally, Section 5 concludes the paper and suggests topics for future research.

2 Literature review

The work of Garbade and Silber (1979) is one of the first studies to evaluate the price discovery process for dually listed equities on the New York Stock Exchange (NYSE) and regional stock exchanges. They stated that a common equilibrium price is verified and found that the NYSE is a dominant market. In the following, Harris et al. (1995) evaluated the price discovery of IBM by analysing the relative contribution of the NYSE and regional exchanges. As the growing number of American Depositary Receipts (ADRs) and Global Depositary Receipts (GDRs) traded on financial markets, the literature have investigated the price-discovery contribution of foreign exchanges to individual stocks.

The price parity convergences for 62 Canadian firms listed on the Toronto Stock Exchange (TSX) and on NYSE were studied by Eun and Sabherwal (2003). The authors indicated that the average US share of contribution was 38.1%, and the US share trading volume and informative trades (bid-ask spreads) are directly (inversely) related to the US share of price discovery. Grammig, Melvin and Schlag (2005) stated a leading role of the German market on the price discovery process of the Frankfurt and the NYSE exchanges for three stocks using high frequency quotes. Price discovery analysis of 64 British and French companies cross-listed on the NYSE is also evaluated in the work of Korczak and Phylaktis (2010).

[4] The literature on the price discovery process of Brazilian cross-listed stock-ADRs are based on linear error correction models using Harris et al. (1995) and/or Hasbrouck (1995) measures as the works of Scherrer (2014), Silveira, Ballini and Maciel (2014) and Kawamoto and Kawamoto (2009).

Regarding five Spanish stocks cross-listed on the NYSE during the daily 2-hour trading overlap of both exchanges, Pascual, Pascual-Fuster and Climent (2006) founded a low NYSE contribution on the corresponding price discovery based on Hasbrouck (1995) information share. Frijins, Gilbert and Tourani-Rad (2010) studied the price discovery of Australian and New Zealand bilaterally cross-listed stocks, and stated that in both cases the home market is dominant in terms of price discovery. However, they also observed that as firms grow larger and their cost of trading in Australia declines, the Australian market becomes more informative. Karolyi (2006) provides a comprehensive survey of studies in the field of global cross-listing. One of his main conclusions is that the home market continues to play a dominant role in the price discovery process for cross-listed stocks but the more recent evidence suggests that the host markets, often the US market, are increasingly influential in price discovery.

Chen, Choi and Hong (2013) is one of the few studies that evaluated the nonlinearities of the price discovery of cross-listed stocks. They proposed a threshold error correction model to gauge the market-respective information shares of Canadian listings traded on the TSX and the NYSE. Empirical findings indicated that parity-convergence accelerates upon discounts on the cross-listings on the NYSE and that informed traders tend to cluster on the NYSE. In addition, information shares and thresholds are affected by the relative degree of private information, market friction and liquidity measures, firm-level characteristics, and aggregate risks (CHEN; CHOI; HONG, 2013).

By employing macroeconomic news announcements as a proxy for new information arrivals, Frijins, Gilbert and Tourani-Rad (2015) examined their impact on price discovery of 38 Canadian companies listed on the TTSX and the NYSE for the period 2004-2011. They observed that price discovery shifts significantly during macroeconomic news announcement days and the NYSE becomes more important in terms of price discovery, regardless of the origin of the news. Ghadhab and Hellara (2016) examined the contribution of cross-listing to price discovery for a comprehensive sample of firms listed abroad. They found that foreign market contribution to price discovery is more important for multiple-listed firms compared to cross-listed ones, and showed that US exchanges are more conductive to price discovery than do foreign European markets.

More recently, Frijins, Indriawan and Tourani-Rad (2018) analyzed price discovery dynamics for Canadian companies cross-listed on the NYSE from January 2004 to August 2017 by employing a structural vector autoregression to assess the interactions between price discovery, liquidity and algorithmic trading activity. The empirical findings indicated that over time, the US market is gaining dominance in terms of price discovery and improvements in liquidity increase a market's contribution to price discovery, and vice versa. Further, the authors evidenced that algorithmic trading activity is negatively related to price discovery, indicating negative externalities of high-frequency trading.

Studies also focused on the price discovery for stocks from emerging markets cross-listed on developed markets. Concerning a Malaysian conglomerate traded both in Kuala Lumpur Stock Exchange (KLSE) and the Stock Exchange of Singapore, Ding et al. (1999) indicated that approximately 70% of the price discovery occurs in the KLSE. Kadapakkam, Misra and Tse (2003) examined the price discovery of Indian stocks dually listed on the London Stock Exchange as Global Depositary Receipts (GDRs). Based on information share estimates of London and Mumbai markets, the authors have achieved that both exchanges contribute almost equally to the price-discovery process.

The price discovery of cross-listing of Chinese companies was also studied in the works of Xu and Fung (2002), Wang and Jiang (2004), and Su and Chong (2007). Generally, the authors showed that the stock prices of different exchanges are cointegrated and mutually adjusting, and that the Stock Exchange of Hong Kong (SEHK) makes more contributions than the NYSE to the price-discovery process, but a significant mutual feedback of information between the two markets was also verified. Wang (2013) investigated whether the price discovery ability of Korean ADRs increases when large movements occur in the US stock market. The authors found an asymmetrical behavior on the price discovery process, as when the US market is stable, the underlying stocks dominate the price discovery process, when it is volatile, regardless of the state of the Korean market, the price discovery process reverses and the trading of ADRs leads to greater price discovery than that of the underlying stocks.

Concerning Brazilian cross-listed stocks, the studies on price discovery are limited. Kawamoto and Kawamoto (2009) studied the double-listing contribution for the price discovery of Brazilian stocks negotiated at the NYSE through ADRs. The work examines whether the prices of stock/ADR pairs have their own common long term relation or, alternatively, whether the prices are cointegrated, and quantifies the contribution of each asset (ADR and stock) in long term price formation through the component share of Eun and Sabherwal (2003). Based on a sample of 32 stocks and their respective ADRs between February 1999 and June 2006, the results showed that in only 15 pairs is there a long-term relationship between stock and its ADR. The results also showed that the parameters of the vector error correction model (VECM) are statistically significant in only two pairs, demonstrating that the necessary adjustments for the maintenance of a long term equilibrium occur in both markets for only 6.25% of the sample.

Using cointegration, causality-in-mean and causality-in-variance tests, Silveira, Ballini and Maciel (2014) investigated the price discovery process of 24 cross-listed stocks of Brazilian companies simultaneously traded on the B3 and NYSE stock exchanges. Authors stated the existence of cointegration for most stock-ADR pairs and that short-term adjustments occurred in both markets. The causality-in-mean and causality-in-variance tests indicated bicausal relationships between the cross-listing prices and variances.

Chiara et al. (2012) identified if there are arbitrage opportunities between Brazilian companies' stocks listed on B3 and theirs ADRs traded on NYSE. Based on 24 stocks with 1-minute trading intervals price on a three-month period, they used t-tests to verify if the absolute value of the differences in prices in BRL Reais of local stocks and theirs ADRs were in average statistically equals to zero. Authors showed that the pairs-trading strategy with stocks and ADRs can generate financial profits, and observed that in less liquid stocks, the maximum transaction cost for the strategy to remain profitable was greater.

Finally, Scherrer (2014) investigated the dynamics of price discovery for cross-listed firms and the impact of exchange rate shocks on firm value based on a two-year high-frequency data set from B3 and NYSE. The author suggested a simple price discovery model in which prices in the home and foreign markets react to shocks on two latent prices, namely, the efficient firm value and the efficient exchange rate. It was found that a depreciation/appreciation of the home currency decreases/increases firm value. This finding is consistent with currency fluctuation affecting discount rates.

The aforementioned literature have shown that there is no consensus concerning whether local or foreign exchange play a more significant role of information transmission in the pricing process of cross-broader listings. Besides mostly of the works suggesting a higher contribution of the local exchanges, the relevance of the foreign exchanges has increased over time. Further, due to market imperfections, price parity adjustments can be better described by a nonlinear approach, as empirically evidenced by Chen, Choi and Hong (2013) and Mitra et al. (2019). Regarding the Brazilian cross-listed stocks negotiated on B3 and NYSE, few studies are provided in the literature, and they are based on linear approaches to evaluate price discovery. Hence, this paper contributes to the literature by assessing the nonlinearities on the price discovery process of Brazilian cross-listings and also considering a larger and recent database of the corresponding stock-ADRs prices.

3 Nonlinear econometric model for price discovery

To evaluate the information role of the US and Brazilian markets for US-Brazilian cross-listed stocks, the contribution of each market to the price discovery process is investigated through a threshold vector error correction model (TVECM). Based on model estimates, the corresponding price discovery measures are computed.

Consider an asset that is traded in two different markets (in the case of this paper, US and Brazil). Let p_t^{US} be the log US dollar price of the security traded in the US market - the New York Stock Exchange (NYSE), and p_t^{BRL} the log US dollar price of the asset traded in the Brazilian market - the São Paulo Stock Exchange (B3). Arbitrage conditions imply that the vector of prices $p_t = (p_t^{US}, p_t^{BRL})'$ should be cointegrated with cointegrating vector $\beta' = (1, -1)$, as the two assets are identical and completely fungible. Hence, price changes can be structured as a standard linear error correction model:

$$\Delta p_t^{US} = \gamma_{10} + \alpha^{US}\kappa_{t-1} + \sum_{i=1}^{l_1} \gamma_{1i}\Delta p_{t-i}^{US} + \sum_{i=1}^{l_2} \tilde{\gamma}_{1i}\Delta p_{t-i}^{BRL} + \epsilon_{1t}, \tag{1}$$

$$\Delta p_t^{BRL} = \gamma_{20} + \alpha^{BRL}\kappa_{t-1} + \sum_{i=1}^{l_1} \gamma_{2i}\Delta p_{t-i}^{US} + \sum_{i=1}^{l_2} \tilde{\gamma}_{2i}\Delta p_{t-i}^{BRL} + \epsilon_{2t}, \tag{2}$$

where $\kappa_{t-1} \equiv p_{t-1}^{US} - p_{t-1}^{BRL}$ can be defined as the dollar premium on the cross-listing (p_t^{US}) on the NYSE against its original listing (p_t^{BRL}, USD-translated) on the B3 (CHEN; CHOI; HONG, 2013), α^{US} and α^{BRL} are the speed of adjustment coefficients for US and BRL prices, which describe the degree of adjustment to the deviation to restore the long-run equilibrium in each series, γ_{ji} and $\tilde{\gamma}_{ji}$ are lagged price coefficients, $j = 1, 2$ and $i = 1, \ldots, l_j$, and ϵ_{jt} are the error terms. Under the specification of the cointegrating vector $\beta' = (1, -1)$, it is expected that $\alpha^{US} \leq 0$ and $\alpha^{BRL} \geq 0$.

To estimate each market contribution to the price discovery, Harris et al. (1995) and Eun and Sabherwal (2003) proposed the use of the error correction model adjustment coefficients to compute the called Component Share (CS), which measures the proportion of the adjustments that takes place on the originally listed exchange out of the total adjustments on both exchanges[5]. The corresponding CS for a security on the B3 and NYSE are calculated as, respectively:

$$CS^{BRL} = \frac{|\alpha^{US}|}{|\alpha^{US}| + \alpha^{BRL}}, \tag{3}$$

$$CS^{US} = \frac{\alpha^{BRL}}{|\alpha^{US}| + \alpha^{BRL}} = 1 - CS^{BRL}. \tag{4}$$

For each market, the lower the speed of adjustment coefficient, the more informative that market is (i.e. a lower response to restore the long-run equilibrium). When $\alpha^{BRL} = 0$ and $|\alpha^{US}| > 0$ ($\alpha^{US} = 0$ and $\alpha^{BRL} > 0$) the Brazilian (US) market is completely dominant and the US (Brazilian) is a pure satellite market. Otherwise, if neither market is completely dominant coefficients $|\alpha^{US}|$ and α^{BRL} will be both positive and their relative magnitudes (component shares) will indicate the degree of dominance of each market.

Transaction costs, direct and indirect trading barriers etc, as market frictions, result in an imperfect market. Following Gagnon and Karolyi (2010) and Chen, Choi and Hong (2013), let us define a threshold δ to measure the sum of transaction costs and risk premiums required from arbitrageurs, i.e. the required arbitrage return. Thus, arbitrage opportunities occur when:

$$\kappa_t \equiv p_t^{US} - p_t^{BRL} < -\delta \text{ or } \kappa_t > \delta, \tag{5}$$

which is similarly as $|\kappa_t| > \delta$.

In this case, p_t^{US} and p_t^{BRL} cointegration is dormant within a range of disequilibrium and the error correction dynamics become active once the cross-listing dollar premium sufficiently diverges from parity beyond the threshold - a regime switching mechanism (CHEN; CHOI; HONG, 2013). Hence, price dynamics can be represented by a threshold error correction model (BALKE; FOMBY, 1997):

$$\Delta p_t^{US} = \begin{cases} \gamma_{110} + \alpha_1^{US}\kappa_{t-1} + \sum_{i=1}^{l_1} \gamma_{11i}\Delta p_{t-i}^{US} + \sum_{i=1}^{l_2} \tilde{\gamma}_{11i}\Delta p_{t-i}^{BRL} + \epsilon_{11t}, & \text{if } |\kappa_{t-1}| \leq \delta, \\ \gamma_{120} + \alpha_2^{US}\kappa_{t-1} + \sum_{i=1}^{l_1} \gamma_{12i}\Delta p_{t-i}^{US} + \sum_{i=1}^{l_2} \tilde{\gamma}_{12i}\Delta p_{t-i}^{BRL} + \epsilon_{12t}, & \text{if } |\kappa_{t-1}| > \delta, \end{cases} \tag{6}$$

[5] Component shares are derived from a permanent transitory decomposition of a vector error correction model (GONZALO; GRANGER, 1995), which is constructed based on an equilibrium framework to characterize the interactive dynamics of a cross-listed pair simultaneously traded on two separate exchanges. For further details refer to Harris et al. (1995) and Harris, McInish and Wood (2002).

$$\Delta p_t^{BRL} = \begin{cases} \gamma_{210} + \alpha_1^{BRL}\kappa_{t-1} + \sum_{i=1}^{l_1} \gamma_{21i}\Delta p_{t-i}^{US} + \sum_{i=1}^{l_2} \tilde{\gamma}_{21i}\Delta p_{t-i}^{BRL} + \epsilon_{21t}, \text{ if } |\kappa_{t-1}| \leq \delta, \\ \gamma_{220} + \alpha_2^{BRL}\kappa_{t-1} + \sum_{i=1}^{l_1} \gamma_{22i}\Delta p_{t-i}^{US} + \sum_{i=1}^{l_2} \tilde{\gamma}_{22i}\Delta p_{t-i}^{BRL} + \epsilon_{22t}, \text{ if } |\kappa_{t-1}| > \delta. \end{cases} \tag{7}$$

The error correction model in (6)-(7) allows gamma coefficients to change conditional on the regime since irrational traders in each market, such as trend or contrarian traders, may look at both prices across the markets. When a large price spread in the outer regime is observed, $|\kappa_{t-1}| > \delta$, the dynamics between current and price past changes is different as traders may switch to a distinct trading habit. In the middle or inner regime, $|\kappa_{t-1}| \leq \delta$, there are neither market forces nor arbitrageurs to sustain the cointegration of the pair of prices (CHEN; CHOI; HONG, 2013; BALKE; FOMBY, 1997). The corresponding component shares according to the inner (CS_1) and outer (CS_2) regimes coefficients are obtained as, respectively:

$$CS_1^{BRL} = \frac{|\alpha_1^{US}|}{|\alpha_1^{US}| + \alpha_1^{BRL}} \text{ and } CS_1^{US} = \frac{\alpha_1^{BRL}}{|\alpha_1^{US}| + \alpha_1^{BRL}}, \tag{8}$$

$$CS_2^{BRL} = \frac{|\alpha_2^{US}|}{|\alpha_2^{US}| + \alpha_2^{BRL}} \text{ and } CS_2^{US} = \frac{\alpha_2^{BRL}}{|\alpha_2^{US}| + \alpha_2^{BRL}}. \tag{9}$$

The threshold error correction model is estimated using the maximum likelihood estimation (MLE) method proposed by Hansen and Seo (2002), assuming that the error term is i.i.d. Gaussian. In addition, threshold δ is estimated using a grid search method[6].

4 Empirical analysis

The aim of this paper is to study the information role in the price discovery process of Brazilian firms cross-listed on the NYSE and B3 stock exchanges by addressing a nonlinear approach to measure parity-convergences through a threshold error correction model, which is a more appropriate methodology for cross-listing price discovery analysis in the presence of market imperfections, as transaction costs, taxes, holding costs, commissions to home and host exchanges, etc. Thus, adjustments to parity, i.e. the long-run equilibrium, are nonlinear allowing for abrupt changes in parity-convergences, dynamic frequently observed in the markets due to risk factors such as information asymmetry and market frictions, which are more relevant in emerging economies like Brazil. In the following subsections the data are described as well as the corresponding econometric analysis, including unit root, cointegration and nonlinear tests, and the corresponding US and BR component shares estimated from threshold error correction models.

4.1 Data

The data are comprised by daily closing prices of Brazilian B3-listed firms that are (or have been) cross-listed on the NYSE[7]. Brazilian B3 quotes were converted in US dollars (USD) using the daily PTAX exchange rate, the average of the buy and sell rate for USD published by the Central Bank of Brazil. Table 1 provides the main information of B3-NYSE stock-pairs considered in this work. Nearly half of the sample (44.4%) concerns stocks related to the industries of oil, gas and biofuels (18,5%), banks (14,8%) and electric utilities (11,1%). For the 24 firms (27 stock-ADR pairs), samples starting date is different, as data are collected considering all the available quotes simultaneously on B3 and NYSE exchanges. All samples end in December 30, 2019 as the results may be affected by the significant consequences on stock prices due to the COVID-19 pandemics[8], resulting on an average of 3,549 observations by stock-ADR pairs.

[6] Hansen (2000) and Hansen and Seo (2002) detail the estimation procedure related to threshold error correction models.

[7] The data were obtained from the Economatica database.

[8] Notice that stock price samples of Cosan under the tickers CZZ (NYSE) and CZLT33 (B3) end on October 10, 2018 as these assets were discontinued on both exchanges.

Table 1 – Sample summary information of Brazilian firms cross-listed on the B3 and NYSE stock exchanges.

Company	Industry	Ticker NYSE	Ticker B3	Type	Start Date	End Date	No. of obs.
Ambev	Beer and soft drinks	ABEV	ABEV3	Common	3/28/01	12/30/19	3,865
Santanter	Banks	BSBR	SANB11	Unit	10/7/09	12/30/19	2,575
Bradesco	Banks	BBDO	BBDC3	Common	3/13/12	12/30/19	1,662
Bradesco	Banks	BBD	BBDC4	Preferred	11/21/01	12/30/19	4,556
Brasilagro	Agriculture	LND	AGRO3	Common	11/8/12	12/30/19	1,452
Braskem	Petrochemicals	BAK	BRKM5	Preferred	12/22/98	12/30/19	4,986
BRF	Food processors	BRFS	BRFS3	Common	4/12/06	12/30/19	3,453
Cemig	Electric utilities	CIGC	CMIG3	Common	6/12/07	12/30/19	2,315
Cemig	Electric utilities	CIG	CMIG4	Preferred	11/4/05	12/30/19	3,561
Copel	Electric utilities	ELP	CPLE6	Preferred	7/30/97	12/30/19	5,642
Cosan	Oil, gas and biofuels	CZZ	CZLT33	Common	8/16/07	7/10/18	2,744
CSN	Oil, gas and biofuels	SID	CSNA3	Common	11/14/97	12/30/19	5,493
Embraer	Aerospace transportation and components	ERJ	EMBR3	Common	6/5/06	12/30/19	3,417
Gerdau	Steel and metalurgy	GGB	GGBR4	Preferred	3/10/99	12/30/19	5,204
Gol	Airlines	GOL	GOLL4	Preferred	6/24/04	12/30/19	3,907
Itau Unibanco	Banks	ITUB	ITUB4	Preferred	2/21/02	12/30/19	4,496
Linx	Software and services	LINX	LINX3	Preferred	6/25/19	12/30/19	131
Oi	Telecommunications	OIBR.C	OIBR3	Common	11/24/09	12/30/19	2,530
Pão de Açúcar	Food retailers	CDB	PCAR4	Preferred	6/2/97	12/30/19	5,685
Petrobras	Oil, gas and biofuels	PBR.A	PETR4	Preferred	9/28/01	12/30/19	4,587
Petrobras	Oil, gas and biofuels	PBR	PETR3	Common	8/10/00	12/30/19	4,876
Sabesp	Water utilities	SBS	SBSP3	Common	5/10/02	12/30/19	4,431
Suzano	Wood and paper	SUZ	SUZB3	Common	12/10/18	12/30/19	265
Vivo	Telecommunications	VIV	VIVT4	Preferred	11/17/98	12/30/19	5,312
Tim	Telecommunications	TSU	TIMP3	Common	8/9/11	12/30/19	2,112
Ultrapar	Oil, gas and biofuels	UGP	UGPA3	Common	9/1/11	12/30/19	2,095
Vale	Metalic minerals	VALE	VALE3	Common	4/15/02	12/30/19	4,460

The performance of these companies at the NYSE is reflected by the Dow Jones Brazil Titans 20 ADR Index, which is designed to measure the 20 largest and most liquid Brazilian stocks traded on major US exchanges as ADRs. Figure 1 shows the temporal evolution of the Dow Jones Brazil Titans for the period from January 2016 to December 2019. Since its launching on 4 October, 2004, with a value of 10,000 points, on 31 December 2019 a significant increase of approximately 157% is observed, with a closing value of 25,678 points, revealing the relevance of these Brazilian ADRs on the US market (see Figure 1). In addition, the 24 firms considered in this work represent a significative equity market capitalization in the Brazilian stock market as they sum together on December 2019 a market value worth of more than USD 550 billions. Due to the relevance on both B3 and NYSE stock exchanges, the study of the corresponding price discovery processes play a central role for market participants.

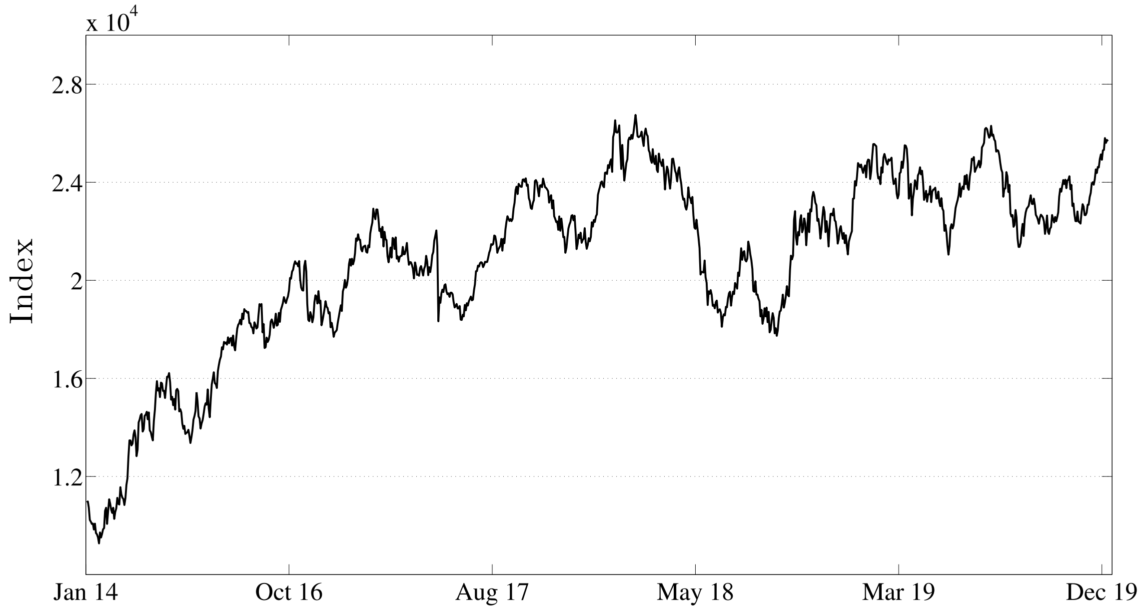

Figure 1 – Dow Jones Brazil Titans 20 ADR Index. Source: Capital IQ.

4.2 Unit root, cointegration and nonlinearity tests

Before estimating the component shares of the firms to evaluate the price discovery process, unit root, cointegration and nonlinearity tests must be conducted. First, the augmented Dickey-Fuller (ADF) (DICKEY; FULLER, 1981) test for each stock and its corresponding ADR is performed, as cointegration concept results only for the case where the stock prices in both markets are non-stationary. Table 2 shows ADF test results for the corresponding log prices as well as for the associated time series in first differences. For the log prices, p_t^{US} and p_t^{BRL}, ADF statistics are not significant for all cross-listed pairs, indicating that the series are nonstationary in level. On the other hand, when log prices are in first differences, Δp_t^{US} and Δp_t^{BRL}, the null hypothesis is rejected for all cases at a 1% significance level, which indicates that log prices are first-order integrated processes, $I(1)$, or unit roots (see Table 2)[9].

[9] ADF unit root test was also computed including a constant and a constant and a trend for the corresponding time series generating process specifications. Results also indicated that log prices are $I(1)$. In addition, the same conclusion was observed using the Kwiatkowski-Phillips-Schmidt-Shin (KPSS) test (KWIATKOWSKI et al., 1992). Statistics are not provided but are available under request.

Table 2 – ADF and Johansen tests results. ADF unit root test statistics are for log prices in level (p_t^{US} and p_t^{BRL}) and in first differences (Δp_t^{US} and Δp_t^{BRL}) of Brazilian firms cross-listed stocks at NYSE and B3. ADF critical values are -1.62, -1.95 and -2.58 for 10%, 5% and 1% significance levels, respectively. ADF corresponding models do not include a constant nor a trend, and the number of lagged values of the series was selected using the Bayesian Information Criteria (BIC) (SCHWARZ, 1978). Johansen test results are from the maximum eigenvalue statistics and the corresponding models do not include a constant nor a trend in the cointegrating relation. Critical values for Johansen test are 12.91, 14.90 and 19.90 (6.50, 8.18 and 11.65) for 10%, 5% and 1% significance levels, respectively, for the null hypothesis of $r = 0$ against $r = 1$ ($r = 1$ against $r = 2$), where r is the number of cointegrating relations. (C) and (P) stand for common and preferred shares, respectively. b is the estimated cointegrating coefficient for the normalized cointegrating vector $\beta' = (1, -b)$ obtained from the Johansen test.

Company	ADF statistics				Johansen statistics		
	p_t^{US}	Δp_t^{US}	p_t^{BRL}	Δp_t^{BRL}	H_0: $r = 0$	H_0: $r = 1$	b
Ambev	-0.2204	-45.3994	-0.2013	-44.6843	814.2184	5.6350	-1.0019
Bradesco (C)	0.1544	-36.0982	0.1350	-28.7113	535.8506	3.5823	-0.9841
Bradesco (P)	0.0362	-48.6570	-0.0092	-46.0480	246.5597	2.6486	-0.9765
Brasilagro	0.2480	-33.2627	0.2397	-26.8789	326.2581	1.8843	-0.9717
Braskem	0.1602	-47.5419	-0.3211	-46.4107	650.2536	6.7761**	-1.0019
BRF	0.0037	-42.2759	0.0062	-40.6594	618.1040	4.5615	-1.0014
Cemig (C)	0.0037	-42.2759	0.0062	-40.6594	292.0394	4.0748	-0.9963
Cemig (P)	-0.4085	-42.7290	-0.4142	-41.5827	49.3191	6.4556	-1.0199
Copel	-0.2530	-52.5480	-0.2393	-51.4841	944.7992	2.3171	-0.9977
Cosan	-0.3174	-45.5463	-0.6618	-44.3687	489.8476	4.1997	-1.0055
CSN	-1.1681	-51.1722	-1.2454	-48.7208	213.2351	2.5002	-0.9917
Embraer	-0.4373	-40.0583	-0.5966	-40.7041	569.4385	6.2460	-1.0055
Gerdau	-0.7232	-50.0875	-0.7718	-48.7523	559.7620	5.9436	-0.9915
Gol	-0.4223	-43.3619	-0.5559	-42.1763	535.0319	1.9656	-1.0064
Itau	0.1348	-30.1679	0.1083	-45.8281	392.5361	2.8146	-0.9972
Linx	-0.1303	-6.9133	-0.1607	-7.4594	50.9199	4.8192	-1.0231
Oi	-2.4082	-34.9038	-1.9330	-33.2884	25.8344	0.2221	-1.0273
Pão de Açúcar	-0.0401	-51.5968	-0.0572	-50.4934	233.8579	3.7309	-1.0281
Petrobras (P)	-0.1016	-48.1701	-0.1016	-45.7876	1064.3684	2.6012	-0.9976
Petrobras (P)	0.0538	-49.3730	-0.1511	-47.8493	587.9808	3.6979	-0.9989
Sabesp	0.7015	-49.0887	0.6549	-48.1512	901.5309	1.7554	-0.9976
Santander	0.1301	-36.3246	0.1977	-35.5976	20.5760	1.1179	-0.9816
Suzano	-0.1938	-12.2314	-0.0751	-11.6794	80.8255	1.7196	-1.0134
Tim	-0.3695	-33.1169	-0.6555	-33.0923	135.6878	3.2773	-1.0109
Ultrapar	-0.3037	-33.0786	-0.2885	-28.0036	640.1613	2.6987	-0.9980
Vale	0.3663	-49.5476	0.3512	-47.8985	873.7905	4.8851	-0.9978
Vivo	0.3493	-51.4681	0.2933	-50.9467	414.4174	1.1887	-0.9831

Note: (**) indicates significance at a 5% level. The remaining ADF and Johansen tests statistics are significant at a 1% level.

As log price series are unit root processes, the Johansen test (JOHANSEN, 1991) for cointegration is performed. Table 2 presents Johansen test maximum eigenvalue statistics for the test of no cointegrating relationship against one cointegrating relationship (H_0: $r = 0$ and H_1: $r = 1$), and for one cointegrating relationship against two cointegrating relationships (H_0: $r = 1$ and H_1: $r = 2$). The results provide statistically evidence for the presence of one cointegrating relationship for all cross-listed pairs at a 1% significance level (except for Braskem where cointegration was confirmed at a 5% significance level)[10]. Table 2 also provides the corresponding estimates of the normalized cointegrating vector $\beta' = (1, -b)$ for each stock-ADR pair[11]. Results indicate that most of the estimated cointegrating vectors are approximately $(1, -1)'$, in accordance to the law of one price. Coefficients b showed a sample mean of $-1,0002$ with standard deviation of $0,0143$. Summing up, all B3-NYSE cross-listed pairs are cointegrated (Table 2).

The cointegration analysis confirmed the law of one price, i.e. the prices of a same asset do not drift far from each other in different markets. However, the convergence dynamics of these prices is not necessarily linear, as market frictions such as transactions costs and short-sale limitations produce nonlinearities to the adjustment mechanisms. Therefore, the relationship of short-run adjustment dynamics to long-run parity equilibrium should be evaluated using a nonlinearity test. Based on the estimation of the symmetric bivariate threshold error correction model described in Section 3 - Eqs. (6)-(7), it is tested the null hypothesis of linear cointegration against threshold cointegration using the supremum-Lagrangian multiplier (supLM) proposed by Hansen and Seo (2002).

Bayesian Information Criteria (BIC) (SCHWARZ, 1978) was considered to determine the number of lags in Eqs. (6) and (7), which consistently resulted in a lag length of 1, i.e. $l_1 = l_2 = 1$. In addition, the model was estimated for each cross-listed pair by maximum likelihood with a cointegrating vector of $\beta' = (1, -1)$. Table 3 provides summary statistics of the nonlinearity test of Hansen and Seo (2002). As suggested by Hansen and Seo (2002), p-values for supLM statistics were computed by parametric bootstrap with 1,000 replications[12]. The null hypothesis of no threshold effect was reject for 22 of the cross-listed pairs at a 5% significance level, which indicates that parity convergence dynamics have a nonlinear behavior (Table 3). For the Ultrapar stock-ADR pair, the null of linear cointegration was rejected at a 10% significance level. For Cosan, Gol, Linx and Suzano firms cross-listed equities, price parity dynamics can be described by a linear error correction model.

A combined p-value test on all firms is also considered to evaluate the threshold effect for prices adjustment dynamics. As proposed by Choi (2001), the corresponding Z-test statistic is computed as:

$$Z \equiv \frac{1}{2\sqrt{N}} \sum_{i=1}^{N} [-2 \cdot \ln(p_i) - 2], \tag{10}$$

where p_i is the asymptotic p-value of the supLM test for a cross-listed pair i, and N is the number of stock-ADR pairs (27 in our case). This statistic is standard normal distributed under the null hypothesis of linear cointegration.

From the results provided in Table 3, the combined p-value test statistic Z is 61.33, which significantly rejects the null hypothesis with a 5% critical value at 1.96, inferring the evidence of nonlinearities on price adjustment dynamics for the whole sample.

[10] Johansen test was also conducted considering the trace statistic and provided similar results. The maximum eigenvalue statistic is preferred for trying to pin down the number of cointegrating vectors as as it has the sharper alternative hypothesis (ENDERS, 2015).

[11] Under the assumption that the two assets are identical and completely fungible, the corresponding dollar premium on the cross-listing is $\kappa_t \equiv p_t^{US} - p_t^{BRL}$. Hence, the Johansen test model specification in this work does not considered a constant nor a trend in the error correction term.

[12] A bootstrap method is used to generate the critical values since the asymptotic distribution is non-standard. Details on the nonlinearity test are found in Hansen and Seo (2002).

Table 3 – Nonlinearity test of Hansen and Seo (2002) for the null hypothesis of linear cointegration against threshold cointegration. The evaluation of a threshold effect considers the supremum Lagrangian multiplier (supLM) test statistic and the corresponding critical values (CV). P-values for supLM statistics are computed by parametric bootstrap with 1,000 replications.

Company	supLM	p-value	90%-ile CV	95%-ile CV	99%-ile CV
Ambev	22.0889	0.0440**	19.0185	20.5654	24.6135
Bradesco (C)	23.8090	0.0329**	19.9513	21.8753	24.4979
Bradesco (P)	111.5243	0.0000***	19.8595	21.8212	25.1615
Brasilagro	24.1013	0.0302**	20.0903	21.6928	24.9123
Braskem	31.1199	0.0032***	19.8484	21.1987	25.0447
BRF	65.7869	0.0000***	19.6564	21.4030	25.9817
Cemig (C)	62.8452	0.0000***	20.4570	22.0375	27.1089
Cemig (P)	72.7497	0.0000***	20.7753	22.8713	25.9369
Copel	38.7653	0.0002***	20.0431	22.2980	25.9540
Cosan	15.3775	0.2844	19.4862	21.7621	25.9509
CSN	138.8259	0.0000***	19.6209	21.4406	26.3335
Embraer	66.4459	0.0000***	20.0207	21.5335	24.9809
Gerdau	28.3637	0.0080***	20.6535	23.1967	26.3949
Gol	12.0204	0.5260	19.2917	20.7436	24.8011
Itau	32.6231	0.0019***	19.8436	21.7618	25.2974
Linx	12.5727	0.4813	17.0472	18.1998	20.2970
Oi	121.5956	0.0000***	19.7603	21.5930	25.5792
Pão de Açúcar	130.1636	0.0000***	20.6998	22.6437	25.0961
Petrobras (C)	76.2418	0.0000***	20.1868	22.1085	24.6899
Petrobras (P)	70.1799	0.0000***	20.0600	21.7672	25.3138
Sabesp	22.6396	0.0462**	20.1059	21.9167	25.6904
Santander	107.5750	0.0000***	20.5874	22.5948	25.9678
Suzano	15.1541	0.2978	18.5999	19.8713	23.3262
Tim	74.4665	0.0000***	20.4988	22.2341	26.5217
Ultrapar	20.8476	0.0802*	20.6685	22.5903	25.7946
Vale	60.0515	0.0000***	20.3626	22.3996	26.5314
Vivo	58.6927	0.0000***	19.4139	21.4448	27.2389

Note: (*), (**) and (***) indicate significance at 10%, 5% and 1% levels, respectively.

4.3 Threshold error correction modeling and price discovery

Due to the statistically evidence of nonlinearities in the price-parity dynamics of the Brazilian cross-listed stocks, price discovery process is studied based on the threshold error correction model estimates for each stock-ADR pair. Table 4 provides threshold estimates and the percentage of the number of observations in each regime (inner and outer regimes). Estimated thresholds measure the required cross-border arbitrage return, i.e. the sum of transaction costs and risk premiums of a cross-border arbitrage (CHEN; CHOI; HONG, 2013). Thresholds range from 0.0003 (Santander) to 1.7147 (Oi) with a mean of 0.2846 and corresponding standard deviation of 0.5157[13]. On average, when the cross-listing dollar premium/discount is more than $\pm$ 0.2846 (estimated threshold - outer regime), i.e. cross-listing dollar premium sufficiently diverges from parity beyond the threshold, arbitrageurs assume positions on both sides, respectively, which drives the deviation back to the "no-arbitrage" band. In comparison with the work of Chen, Choi and Hong (2013), for Canadian firms cross-listings, it is interesting to note that, for the Brazilian cross-listed stock-ADR pairs, the cross-listed dollar premium is significantly higher: the dollar premium average for Canadian firms cross-listings was 0.1930, indicating that the sum of transaction costs and risk premiums of a cross-border arbitrage are higher for trading with Brazilian asset pairs (0.2846). Moreover, threshold estimates at a 99%

[13] The minimum estimated threshold was 0.0001 from Ultrapar cross-listed pair. However, for this case the supremum Lagrangian multiplier test indicates no statistically significant evidence of a regime switching dynamic for the parity convergence process (see Table 4), which compromises the proper interpretation of the required cross-border arbitrage return.

percentile for Canadian firms was 0.8970 according to Chen, Choi and Hong (2013), against 1.6741 for the Brazilian firms (Table 4), confirming that, for an emergent economy like Brazil, arbitrageurs required a higher cross-border arbitrage return, revealing a higher influence of market frictions.

The percentage of data falling into the inner and outer regimes are also presented in Table 4. On average, 33.45% of the data falls into the outer regime, with a standard deviation of 30.77%. Again, Chen, Choi and Hong (2013) observed, for Canadian firms cross-listings, an average of 17% of the data falling into the outer regime. The outer regime is related to when the cross-listing dollar premium sufficiently diverges from parity beyond the threshold, indicating that the price spread is large and traders may switch to another trading habit, driving dynamics to parity. Therefore, the results indicated that significant divergences of price parity occur in a frequency for Brazilian cross-listed firms almost twice than for Canadian stock-ADR pairs, which shows more arbitrage opportunities when trading Brazilian equities simultaneously listed at NYSE and B3. For Ambev, Brasilagro, Braskem, BRF, Cemig (common shares), Copel, CSN, Pão de Açúcar, Sabesp and Vale, the percentage of data falling in the outer regime is higher than 70%, evidencing a significant presence of divergences on price-parity, thus arbitrage opportunities for cross-border traders when negotiating their corresponding stock-ADR pairs.

Table 4 – Threshold estimates from a bivariate two-regime switching error correction model, and the corresponding number of observations percentages in each regime (inner and outer). The models were estimated by maximum likelihood with a cointegrating vector of $\beta' = (1, -1)$ and a lag length of 1 for both lagged prices ($l_1 = l_2 = 1$).

Company	Threshold	Inner Regime %-age	Outer Regime %-age
Ambev	0.0108	0.9346	0.0654
Bradesco (C)	0.0046	0.6558	0.3442
Bradesco (P)	0.0103	0.6146	0.3854
Brasilagro	0.0372	0.9500	0.0500
Braskem	0.6545	0.7778	0.2222
BRF	0.0221	0.9413	0.0587
Cemig (C)	0.0560	0.8355	0.1645
Cemig (P)	0.0366	0.3050	0.6950
Copel	0.0193	0.8922	0.1078
Cosan	0.0129	0.9410	0.0590
CSN	0.0022	0.9432	0.0568
Embraer	1.3713	0.0508	0.9492
Gerdau	0.0111	0.5827	0.4173
Gol	0.7143	0.8785	0.1215
Itau	0.0386	0.6985	0.3015
Linx	0.0002	0.9440	0.0560
Oi	1.7147	0.1103	0.8897
Pão de Açúcar	0.0126	0.9364	0.0636
Petrobras (C)	0.6560	0.2425	0.7575
Petrobras (P)	0.6878	0.0911	0.9089
Sabesp	0.0185	0.9433	0.0567
Santander	0.0003	0.3128	0.6872
Suzano	0.0078	0.9087	0.0913
Tim	1.5587	0.3234	0.6766
Ultrapar	0.0001	0.6818	0.3182
Vale	0.0187	0.9162	0.0838
Vivo	0.0066	0.5468	0.4532

Estimates of the speed of adjustment parameters to the deviation to restore the long-run equilibrium for US and Brazilian cross-listed prices are shown in Table 5, based on the linear error corrections models (ECM) - Eqs. (1)-(2), and on the two-regime threshold ECM - Eqs. (6)-(7). When α^{US} (α_1^{US} and α_2^{US}) is (are) not statistically significant, and $\alpha^{BRL} > 0$ ($\alpha_1^{BRL} > 0$ and $\alpha_2^{BRL} > 0$), the US market is completely dominant (in the inner and outer regimes). Otherwise, Brazilian market is completely dominant (for inner and outer regimes) when $|\alpha^{US}| > 0$ ($|\alpha_1^{US}| > 0$ and $|\alpha_2^{US}| > 0$) and $\alpha^{BRL} = 0$ ($\alpha_1^{BRL} = 0$ and $\alpha_2^{BRL} = 0$). For the 23 cross-listed pairs that showed statistically evidence of nonlinearities on price adjustment dynamics according to supLM statistics, the results from Table 5 indicate that for the inner and outer regimes, the Brazilian (US) market is dominant in 30.4% and 43.48% (13.0% and 13.1%) of stock-ADR pairs, respectively, inferring that in both price parity dynamics the local exchange plays a more important role in price discovery. In addition, both markets influence price discovery, i.e. play a relative informationally dominance, for the inner and outer regimes, respectively, in 56.5% and 34.8% of the evaluated Brazilian stock-ADR pairs, as $|\alpha_1^{US}|$, $|\alpha_2^{US}|$, α_1^{BRL} and α_2^{BRL} are all positive and statistically significant. Finally, for the cases when a linear cointegration was observed, linear ECM speed of adjustment estimates indicated that for Linx and Cosan firms the US market is informationally dominant for the stock-ADR prices dynamics, whereas for Gol and Suzano both exchanges have a certain degree of dominance in the price discovery processes (Table 5).

In order to measure the contribution of each market (B3 or NYSE) to the price-parity dynamics, the corresponding component shares (CS) were computed using both linear and threshold error correction models. CS estimates are provided in Table 6. In the works of Eun and Sabherwal (2003) e Chen, Choi and Hong (2013), both concerning Canadian cross-listed stock pairs, the authors achieved that NYSE component shares showed a mean of approximately 40%, using a linear ECM. Also considering the standard linear ECM model, results from Table 6 indicated that CS^{US} has a mean of 47.14%, which provides consistent conclusion with the literature, i.e. price discovery for most cross-listed pairs occurs in the local exchange. B3 componente shares (CS^{BRL}) showed a mean of 52.86% based on linear ECM which means that, even the leading role of B3 to the price discovery, there is a significant feedback from the NYSE.

However, as shown in subsection 4.2, there is a statistically evidence of nonlinearities on the price-parity dynamics for Brazilian firms, thus linear ECM estimates may be biased. Based on the results reported in Table 6 obtained from the threshold error correction models, component share estimates of the NYSE (B3) in the inner regime, CS_1^{US} (CS_1^{BRL}), range from 1.23% to 98.69% (1.31% to 98.77%), with an average of 44.76% (55.24%). Hence, B3 makes a larger contribution to price discovery process in the inner regime. Chen, Choi and Hong (2013), for Canadian cross-listed firms, have achieved an average of 36.2% for the NYSE component share using also a nonlinear framework. Thus, in the inner regime, concerning the firms of an emergent economy like Brazil, the foreign exchange (NYSE) plays a more significant role in the price discovery process for the stock-ADR pairs compared to Canadian cross-listings.

Regarding the outer regime, based the corresponding component shares in Table 6, CS_2^{US} and CS_2^{BRL} range from 12.52% to 99.95% and from 0.05% to 87.48%, respectively. In addition, the information contributions of NYSE and B3 to the price discovery process showed an average of 35.24% and 64.76%, respectively. Thus, the contribution of B3 to parity convergences in the outer regime is higher than the NYSE for the Brazilian cross-listed firms. In addition, the local exchange (B3) showed a more informative role in the outer regime when compared to the inner regime, which differs from the empirical evidence of Chen, Choi and Hong (2013), when Canadian cross-listed pairs were taken into consideration. Chen, Choi and Hong (2013) showed that NYSE makes a larger contribution to price discovery in the outer regime. As pointed out by Fremault (1991), arbitrageurs generally focus the market when price deviations are sizable, and their arbitrage activities transfer information from the home market to the NYSE. Hence, this information flows to NYSE show to be more significant for Brazilian cross-listed pairs in the outer regime than for Canadian firms stock-ADR prices dynamics. Finally, as the cross-listing dollar premium sufficiently diverges from parity beyond the threshold (outer regime), the information role by both exchanges is significantly different from the inner regime for the Brazilian cross-listed pair, indicating the importance of allowing nonlinearities to the price discovery process through a threshold error correction modeling framework.

Table 5 – Speed of adjustment coefficients estimates for US and Brazilian cross-listed prices from bivariate linear error correction models (ECM) (α^{US} and α^{BRL}) and from bivariate two-regime threshold ECM (α_1^{US} and α_1^{BRL} correspond to the inner regime, and α_2^{US} and α_2^{BRL} to the outer regime).

Company	Linear ECM				Threshold ECM							
	α^{US}		α^{BRL}		α_1^{US}		α_1^{BRL}		α_2^{US}		α_2^{BRL}	
	Estimate	St. error	Estimate	St. error	Estimate	St. error	Estimate	St. error	Estimate	St. error	Estimate	St. error
Ambev	-0.3302***	0.0368	0.2237	0.0359	-0.2270***	0.0465	0.3546***	0.0455	-0.6231***	0.1002	0.0386	0.0980
Bradesco (C)	-0.8015***	0.0470	0.0272	0.0360	-0.8977***	0.0810	0.0517	0.0620	-0.9156***	0.0797	-0.0646	0.0610
Bradesco (P)	-0.1434***	0.0277	0.0172	0.0249	-0.4538***	0.0815	0.1763***	0.0734	-0.0366	0.0229	-0.0225	0.0206
Brasilagro	-0.5448***	0.0332	-0.017	0.0273	-0.4707***	0.0358	0.0184	0.0293	-1.0228***	0.1779	-0.4102***	0.1455
Braskem	-0.3185***	0.0288	0.0297	0.0285	-0.3860***	0.0450	0.0048	0.0445	-0.4194***	0.0555	-0.2147***	0.0549
BRF	-0.3114***	0.0515	0.2043***	0.0475	-0.3019***	0.0604	0.2028***	0.0557	-1.1248***	0.2687	0.0246	0.2480
Cemig (C)	-0.3143***	0.0270	0.0123	0.0243	-0.2505***	0.0337	-0.0084	0.0304	-0.7293***	0.0918	-0.0729	0.0826
Cemig (P)	-0.0135	0.0163	0.0290*	0.0154	-0.1699***	0.0531	-0.1922***	0.0498	-0.0817*	0.0466	0.0792*	0.0436
Copel	-0.1725***	0.0341	0.2843***	0.0328	-0.1654***	0.0466	0.3311***	0.0447	0.2446**	0.1040	0.7204***	0.0998
Cosan	0.0048	0.0367	0.4318***	0.0329	0.0054	0.0387	0.4049***	0.0349	-0.2245	0.1436	0.4281***	0.1295
CSN	-0.0805***	0.0170	0.0265***	0.0163	-0.1433***	0.0356	0.1746***	0.0342	0.0618*	0.0372	0.0359	0.0358
Embraer	0.0129	0.0500	0.4817***	0.0492	1.3910***	0.2634	2.2531***	0.2586	-0.0511	0.0549	0.3568***	0.0539
Gerdau	-0.2427***	0.0298	0.0572**	0.0288	-0.3332***	0.0753	0.0856	0.0726	-0.1459***	0.0392	0.0346	0.0378
Gol	-0.1289***	0.0458	0.2518***	0.0424	-0.1810***	0.0503	0.1357***	0.0465	0.3510*	0.1909	0.9886***	0.1766
Itau	-0.1624***	0.0369	0.0917***	0.0333	-0.0704	0.0594	0.1911***	0.0536	-0.2149**	0.0974	0.1003	0.0880
Linx	0.3959	0.4617	1.3414***	0.4374	0.1877	0.4840	1.0520***	0.4691	6.8871	7.2144	7.9302	6.9923
Oi	-0.0105	0.0104	0.0188**	0.0094	-0.2113*	0.1205	-0.0789	0.1090	-0.2815***	0.0458	0.2243***	0.0414
Pão de Açúcar	-0.0080	0.0180	0.1087***	0.0167	-0.0192	0.0149	0.0471***	0.0139	-0.6326***	0.2732	0.0608	0.2556
Petrobras (C)	-0.3167***	0.0580	0.2883***	0.0546	-0.8600***	0.1708	0.3121*	0.1609	-0.2050***	0.0742	0.2428***	0.0699
Petrobras (P)	-0.1787	0.0500	0.1910***	0.0460	-0.5238**	0.2601	0.8274***	0.2390	-0.0648	0.0580	0.2198***	0.0533
Sabesp	-0.2409***	0.0469	0.3200	0.0453	-0.1992***	0.0525	0.2986***	0.0507	-1.3057***	0.2727	-0.2452	0.2636
Santander	-0.0226	0.0142	0.0021***	0.0137	-0.0472	0.1519	0.4915***	0.1455	0.0133	0.0195	0.0066	0.0186
Suzano	-0.6014***	0.1743	0.0842***	0.1591	-0.7661***	0.3432	0.0397	0.3124	-1.0715***	0.2854	-0.5699**	0.2598
Tim	0.0262	0.0412	0.2129	0.0403	-0.7546***	0.2030	0.1515	0.1995	0.0566	0.0509	0.1272***	0.0500
Ultrapar	-0.2616***	0.0854	0.5379***	0.0804	-0.3600***	0.1327	0.5357***	0.1249	-0.3596*	0.1950	0.3961**	0.1835
Vale	-0.2175***	0.0572	0.3321	0.0535	-0.2173***	0.0658	0.2815***	0.0616	-0.7455***	0.2527	0.3161	0.2365
Vivo	-0.0860***	0.0184	0.1302***	0.0178	0.1130***	0.0473	0.3803***	0.0454	-0.0741***	0.0227	0.0610***	0.0218

Note: (*), (**) and (***) indicate significance at 10%, 5% and 1% levels, respectively.

Table 6 – Component shares (CS) of B3 (BRL) and NYSE (US) stock exchanges for Brazilian cross-listed stocks for linear and threshold error correction models. The component share is a relative measure of the contribution by each exchange to the price discovery process of B3-US cross-listed pairs. From the bivariate two-regime error correction model (threshold ECM), CS are computed for the inner and outer regimes, CS_1 and CS_2, respectively.

Company	Linear ECM		Threshold ECM			
			Inner regime		Outer regime	
	CS^{BRL}	CS^{US}	CS_1^{BRL}	CS_1^{US}	CS_2^{BRL}	CS_2^{US}
Ambev	0.5964	0.4036	0.3903	0.6097	0.9416	0.0584
Bradesco (C)	0.9671	0.0329	0.9455	0.0545	0.9759	0.0241
Bradesco (P)	0.8920	0.1080	0.7201	0.2799	0.9995	0.0005
Brasilagro	0.9696	0.0304	0.9625	0.0375	0.9670	0.0330
Braskem	0.9156	0.0844	0.9877	0.0123	0.9486	0.0514
BRF	0.6039	0.3961	0.5982	0.4018	0.9786	0.0214
Cemig (C)	0.9624	0.0376	0.9356	0.0644	0.9111	0.0889
Cemig (P)	0.3112	0.6888	0.7649	0.2351	0.5077	0.4923
Copel	0.3775	0.6225	0.3332	0.6668	0.2535	0.7465
Cosan	0.0109	0.9891	0.0131	0.9869	0.3440	0.6560
CSN	0.7498	0.2502	0.4508	0.5492	0.6328	0.3672
Embraer	0.0262	0.9738	0.3817	0.6183	0.1252	0.8748
Gerdau	0.8093	0.1907	0.7956	0.2044	0.8085	0.1915
Gol	0.3386	0.6614	0.5716	0.4284	0.2620	0.7380
Itau	0.6387	0.3613	0.2691	0.7309	0.6817	0.3183
Linx	0.2280	0.7720	0.1514	0.8486	0.4648	0.5352
Oi	0.3582	0.6418	0.8953	0.1047	0.5565	0.4435
Pão de Açúcar	0.0687	0.9313	0.2898	0.7102	0.9123	0.0877
Petrobras (C)	0.5235	0.4765	0.7337	0.2663	0.4578	0.5422
Petrobras (P)	0.4828	0.5172	0.3876	0.6124	0.2276	0.7724
Sabesp	0.4299	0.5701	0.4001	0.5999	0.9313	0.0687
Santander	0.9046	0.0954	0.0875	0.9125	0.6678	0.3322
Suzano	0.8769	0.1231	0.9507	0.0493	0.8936	0.1064
Tim	0.1095	0.8905	0.8328	0.1672	0.3079	0.6921
Ultrapar	0.3273	0.6727	0.4019	0.5981	0.4759	0.5241
Vale	0.3955	0.6045	0.4357	0.5643	0.7022	0.2978
Vivo	0.3981	0.6019	0.2291	0.7709	0.5486	0.4514

5 Conclusion

Due to the increasing number of firms that have cross-listed their shares on foreign exchanges, the analysis of the relative importance of the different markets on the corresponding price discovery processes is worth examining. This paper have studied price-parity contributions of the B3 and NYSE stock exchanges for 27 Brazilian cross-listed stocks using threshold cointegration error correction models, as the adjustment to parity can be nonlinear due to market frictions such as transaction costs and associated risk premiums of arbitrage. Empirical findings provide the following implications: i) all cross-listed pairs showed statistically evidence for the presence of one cointegrating relationship, i.e. a common long term relation is verified, in accordance to the law of one price since the stock prices are based on the same underlying asset; ii) price adjustment dynamics are mostly nonlinear, as the null hypothesis of no threshold effect was rejected for 23 of the stock-ADR pairs; iii) the required cross-border arbitrage return for Brazilian cross-listed firms, measured by the estimated thresholds, is higher, on average, when compared against Canadian cross-listings, revealing a more significant influence of market frictions and a higher frequency of divergences on price-parity for dual-listed stocks from firms of emergent economies like Brazil; iv) component share estimates have indicated that B3 makes a larger contribution to price discovery process and, for the outer regime, when the price gap exceeds the threshold (required arbitrage return), the informationally dominance of the local exchange (B3) is even more significant. Future works shall include the analysis of the corresponding component shares over time as well as the evaluation of the possible factors determining the scope of market influences on the price discovery of the cross-listed pairs and the effective required returns to arbitrageurs.

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