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Contagion effects in ASEAN-5 exchange rates during the Covid-19 pandemic

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ABSTRACT

The aim of this study is to examine the pure and fundamentals-based contagion effects in ASEAN-5 exchange rates during Covid-19 period using daily exchange rates from June 2019 to December 2020. We adopt VECM within the structural VAR framework and higher time–frequency wavelet analysis. The VECM findings show that ASEAN-5 exchange rates are cointegrated during this pandemic and should there be any disequilibrium, daily rate of adjustments in the Indonesian rupiah, Malaysian ringgit and Singapore dollar are 6.58%, 1.47% and 2.45% respectively. The wavelet power spectrum implies that Indonesia, Malaysia and Singapore experience prolonged high degree of exchange rates volatility, Thailand experiences mild volatility in the short run and high volatility in the long run and only Philippines experiences mild volatility in the short run and no heightened long run volatility. The wavelet coherence shows Indonesian rupiah reacts first to the Covid-19 shock leading to fundamentals- based contagion to Malaysia and Thailand, and temporary pure contagion based on sentimental to Philippines and Singapore. Only the Philippine peso that insulates itself from the long run shocks. These findings are important as it gives insights into the nature of contagion among ASEAN-5 exchange rates due to global shock of Covid-19 and the need for timely intervention to prevent the short run contagion turning into the long run.

1. Introduction

The ebb and flows of Covid-19 infections along with the frequency and severity of lockdowns have raised concerns among emerging market and developing economies on the vulnerability of their currencies as national debt surge and growth plunge down. Covid-19 is a global shock that have triggered adjustments in international financial markets. Using the concept of contagion which is the intensification or increase in the spill over of a particular shock from one asset price to another asset price (Apergis and Christou, 2017), this study attempts to identify empirically the existence of exchange rates contagion among ASEAN-5 during this pandemic and the type of contagion in terms of pure-contagion (short-run) or fundamentals-based contagion (long-run).

Kollias et al. (2011) and Baker et al. (2020) illustrate that any exogenous shocks (e.g. outbreak announcement) are deemed to be infiltrated in terms of return and volatility in the financial markets and the severity is pronounced as 'black swan event'. Cheong et al. (2020) confirms that financial market radiates signs of reversal with regards to the COVID-19 events that protrudes negativity connotation.

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According to Dewandaru et al. (2017), contagion effect can be classified into two broad categories: pure contagion or fundamentals-based contagion. Pure contagion is defined as an excessive transmission shock that is beyond the idiosyncratic and fundamental risks, which affects the short-term volatility without any effects on long-term trend (Forbes and Rigobon, 2002; Eichengreen et al., 1996). This usually happen because of investors or financial agents' irrational behaviour such as financial panics, herd behaviour, loss of confidence and increased risk aversion. On the contrary, fundamentals-based contagion can be transmitted through common shocks and common creditors, trade linkages, regional patterns, macroeconomic similarities, or financial market integration which tends to shift the long-term trend (Pesenti and Tille, 2000; Calvo and Reinhart, 1996). Instead of looking at these two views as opposing, Pesenti and Tille (2000) suggested that they should complement each other to create a comprehensive picture of contagion in exchange rate markets. According to them, a country's pre-existing fundamental weaknesses will adversely affect the market sentiments and lead to confidence crisis that will further deteriorate its economic conditions. These self-fulfilling expectations and investors panic along with weak economic fundamentals are the crux to the genesis and spread of a crisis (Pesenti and Tille, 2000). Furthermore, transmission of shocks not necessarily happen from one country to its regional neighbours but can be seen as initial disturbances being replicated by several countries due to common shocks. For example, ASEAN-5 countries share common features of stable exchange rate against the U.S. dollar as the U.S. is one of the ASEAN's largest trading partners. Hence, any shocks to the U.S. dollar as the anchor currency to ASEAN-5 is deemed as common shocks that can increase the vulnerability of ASEAN-5 countries' exchange rates (Klyuev and Dao, 2016).

For ASEAN-5 countries, the exchange rate regimes vary. According to IMF (2015) classification, Indonesia, the Philippines, and Thailand are floaters since these countries profess floating exchange rates. On the contrary, Malaysia and Singapore's exchange rate regimes are classified as managed floating since they monitor the value of their currencies against an undisclosed basket of currencies and intervene in the market to ensure the currencies move within an undisclosed target band (Klyuev and Dao, 2016). However, the monetary authorities of these ASEAN-5 countries do acknowledge their intervention in foreign exchange markets is to smooth excess volatility and not targeting any specific level of the exchange rates.

There are two main contributions of this research to the existing literature. First, this research is timely as it is among the earliest to examine the contagion effect in ASEAN-5 exchange rate markets during the ongoing Covid-19 pandemic. ASEAN-5 region is chosen as it is the fifth largest region by GDP in the world amounting to USD 2.77 trillion in 2017 with growth rate of 5–6% per annum (Aprilianti, 2019). These emerging countries are also known as 'tiger cub economies' in recognition to their similarity to ASIAN economic powerhouse of South Korea, Taiwan, Hong Kong and Singapore. Historically, it is known to have stellar economic performance due to its sustained economic growth since 1960 (Sarel, 1997) and its success in weathering the Asian Financial Crisis (AFC) in 1997, SARS in the 2000s, and the Global Financial Crisis (GFC) in 2007 (Abdullah and Siddiqua, 2015). Unlike those previous crises, the successive and cascading effect of Covid-19 has caused perilous disruption in global value chain on both supply and demand side. The restrictions on cross border mobility motivated by health reason have heavy impact on international trade and investments (Saurav et al., 2020) which can potentially expose countries to foreign exchange risks. According to Kumar and Persaud (2002), reduced in trade competitiveness can cause devaluation of currency that can trigger speculative attacks in the exchange rate equilibrium. This is evidenced during AFC 1997/98 and Mexican crises in 1994 where Khan (2018) have shown that strong trade linkages among countries to the 'first victim country' either through bilateral trade or export competition see significant depreciation and lost reserves during the crises. Hence, in the absence of global efforts and the dire need for governments to quickly act in containing the Covid-19 worldwide, the rising financial volatility can heighten the currency contagion formation and transfer of uncertainty from one economy to another. The presence of contagion effects has empirically shown to exist among ASEAN-5 countries during AFC and GFC (Hurley and Santos 2001, Lee and Azali, 2010), however, no consensus emerged on the type of contagion.

Second, this research combines econometric techniques of vector error correction model (VECM) in the structural VAR framework and multi scale wavelet analysis. These two econometric techniques complement our findings in such that the former captures short and long run impact of exchange rates co-movement while the latter provides the specific timing, frequency, coherence and the origin country of the contagion effect. The results of the paper indicate that in both period of pre and during the Covid-19, there exists cointegration among ASEAN-5 exchange rates and only a few statistically significant exchange rate pairs in the short run. The VECM also reveals that should there be any shocks to the exchange rates, Indonesian rupiah, Malaysian ringgit and Singapore dollar appear to be the important bearers of short run adjustments to a long run equilibrium in the region as shown by the error correction term (ECT) whereby the volatilities are dampen at rates of 6.58%, 1.47% and 2.45% of daily adjustment respectively. The BIC and transfer entropy ratios further show significant reduction in bilateral relationship from pre Covid-19 period to more of unilateral relationship and isolated states during Covid-19. The wavelet power spectrum highlights heightened short and long run volatilities in Indonesia, Malaysia, and Singapore exchange rates during this pandemic while the Philippines only experiences minimal short run volatility. We also observe that Thailand experiences minimal short run but heightened long run volatility. The wavelet coherence then shows heightened degree of co-movement among these countries with Indonesia leading in both short run and long run.

The findings are important as it highlights the vulnerability in ASEAN-5 fundamentals that can turn short-run market sentiment contagion into the long run contagion effect which will prolong the economic recovery post pandemic. Furthermore, the rate of exchange rate daily adjustments offers insights to investors and financial agents in their portfolio diversification decision. Realizing that ASEAN-5 central banks will intervene to dampen any excessive volatility in their exchange rates which can deplete their international forex reserve quickly, identifying the type of contagion can offer suggestions to policy makers on the appropriate intervention to adopt and the timing of the intervention. Too late intervention can cause short term contagion effect to spill over to a long one. For foreign investors, the results offer insights into the diversification of their investment portfolios. Investments in countries where the currencies continue to be volatile since the inception of the pandemic may offer insights into the fundamentals of the particular country.

This paper is organized as follows: Section 2 discusses the theoretical and empirical literature on currency contagion. Section 3 presents empirical methodologies of VECM and wavelet analysis. Section 4 discusses the results. Section 5 provides the policy conclusion.

2. Literature review

There are two strands of literature that are relevant to our study here: First is the theoretical development underpinnings the pure contagion versus fundamentals-based contagion supported by the evidence of ASEAN-5. Second is the established methodologies used in measuring the contagion across financial markets.

2.1. Pure contagion versus Fundamental-Based contagion in currency market

The theoretical development of contagion can be traced back to the three generation models of currency crisis contagion. The first-generation model (Krugman, 1979) has argued that a country with fixed exchange rate regime but weak domestic fundamentals i.e., high fiscal deficits can lead to excessive expansionary monetary policy to finance the deficits that eventually offers a fertile ground for speculators to attack its currency. In the second-generation model (Obstfeld,1994), it is arguable that although a country may have good fundamentals, the exogenous shocks of market psychology either through self-fulfilling prophecy, herding behaviour or cascading information can cause investors to downplay national specificity and asymmetries and consider several countries in a region to be substantially homogeneous. The third-generation model (Mckinnon and Pill, 1997; Krugman,1998) shows currency mismatch and maturity mismatch arise from financial liberalization and over leverage syndrome (Maroney, Naka and Wansi, 2004) can contribute to a country's currency crisis. Subsequent theoretical literature on pure contagion (market psychology) include Dornbusch (1976), Kaminsky and Reinhart (2000), Forbes and Rigobon (2002) and Eichengreen et al. (1996). Fundamental causes of contagion can permeate from common shocks (Calvo and Reinhart, 1996); trade linkages and competitive devaluations (Corsetti et al, 2000) and financial linkages (Kaminsky and Reinhart, 1999).

Over the years, there have been many studies that have tried to classify the type of contagion that happen during crises period. For a similar crisis, the classification can vary depending on many factors especially the methodology used, the period in which the crisis is covered, the countries affected and many others. For example, Caramazza, Ricci and Salgado (2000) find the insignificant of trade contagion during AFC 1997/98 and Mexican crisis 1994. However, when interaction term of trade and current account deficit is introduced, the trade variable is significant. On the other hand, study by Khan (2018) shows the significant of trade channel during similar crises when trade is defined as export competitiveness to the third country.

One of the empirical evidences used to justify the type of contagion was the AFC 1997/98. During the period of AFC, studies on ASEAN currency markets by Hurley and Santos (2010) and Lee and Azali (2010) conclude the existence of contagion originated from Thailand as a result of greater variance decomposition during the crisis and Granger causation from Thailand to other ASEAN countries. April et al. (2008) finds a similar conclusion that there is a significant increase of cross-country correlations in five Asian stock markets (Singapore, Thailand, South Korea, Taiwan, and Malaysia) during AFC. The rising co-movement was due to sudden nature reflecting pure contagion effects rather than gradual adjustments suggesting financial interdependence. On the contrary, when Forbes and Rigobon (2002) remove heteroscedasticity bias from correlations, they find small evidence of co-movement during AFC and conclude that this is merely interdependence rather than pure contagion. Meng and Huang (2019) also detect different degree of financial interdependence among ASEAN economies when they examine the variables at lower and higher frequencies. Park and Song (2001) also shows evidence that AFC did not trigger the crisis in South Korea because the contagion effect is very minimal. The most recent study on currency linkages by Qureshi and Aftab (2020) covering the period of GFC shows the existence of contagion for Indonesia that lag all other ASEAN countries during the crisis period. However, these ASEAN countries show significant greater inter dependency at lower-level frequency (long run) which reaffirm the evidence of financial interdependence rather than pure contagion effect.

Our paper contributes to the existing literature by identifying the type of contagion (if any) that arise during the ongoing pandemic among ASEAN-5 countries. Unlike previous studies on currency contagion shocks that initiated from the financial linkages/macro-economic variables, the current Covid-19 was unprecedented public health emergency. Does the type of currency contagion still prevail during this intertwined health care crises?

2.2. Empirical methodologies to measure contagion

In terms of the methodology used to analyse the exchange rate inter-dependency and contagion, many of the studies have used cointegration tests to find long run relationship among exchange rates (Kuhl 2010; Jeon and Lee 2002). The idea is that any short run deviation without shifting apart the long-term state is deemed as a pure contagion effect. According to Dewandaru et al. (2017), this means that pure contagion shock can only increase the short-run correlation without any changes in the long-run correlation while fundamentals-based shocks can increase both the short-run and long-run correlation. Other studies use Granger causality between exchange rates (Nikkinen et al. 2011) to detect the presence of contagion during the period of calamities; principal component analysis that decomposes exchange rates into distinctive component and a common factor (Beckmann et al., 2012); generalized autoregressive conditional heteroscedasticity (GARCH) model to observe volatility spill over among different currencies (Tamakoshi and Hamori, 2014); wavelet analysis that allows the investigation of financial interdependence and contagion across time and frequency (Qureshi and Aftab, 2020; Meng and Huang, 2019); spatial econometrics (Frexedas and Vaya, 2005) and panel probit model (Salgado et al., 2000) that identify common creditor and reserve adequacy as the main factors that propagate the contagion effect. Since some of these empirical techniques suffer from heteroscedasticity problem in their correlation estimate, the testing of contagion effect can be biased (Dewandaru et al., 2017; Forbes and Rigobon, 2002). The existence of heteroscedasticity bias means volatility effect is static and will not affect low and high time scale correlations differently (Forbes and Rigobon, 2002). In addition, the econometrics techniques only have standard time domain instruments that make it hard to distinguished fundamental-based contagion versus other shocks transmission.

To overcome the mentioned problems above, Bodart and Candelon (2009) has proposed that a study on contagion needs an empirical method that can associate high and low frequencies to distinguish the two types of contagion. This concept can be applied using wavelet analysis (Dewandaru et al., 2017) that partition based on time, coherence and frequency bands in such that the dynamics co-movement of contagion can be analysed without loss of information. Furthermore, the wavelet analysis is very sensitive to high frequency data that makes it more suitable in the analysis where we will have larger time scales to examine the dynamics of co-movement of two markets (Dewandaru et al, 2017). Our study applies the same concept by using wavelet multi-scale analysis that can avoid heteroscedasticity bias when the volatility is allowed to affect both low and high time scale correlations (Forbes and Rigobon, 2002) and across different frequency bands (Dewandaru et al. 2017). In addition to examining this dynamism, we supplement with econometrics technique of VECM to calculate the magnitude and speed of adjustment in the exchange rate market across ASEAN-5 when cointegration exists. The robustness of these findings are cross-checked using variance decomposition method following Hurley and Santos (2000) and Lee and Azali (2000).

As an unclear debate pertaining to pure contagion versus fundamental-based contagion progress, our second contribution to this pool of literature is to investigate empirically the evolution of short and long-run exchange rates contagion pre and during the Covid-19 pandemic. We have used daily data from June 2019 to December 2020 whereby WHO (2020) official announcements are used as the break point for crisis period. Instead of looking at pure contagion and fundamentals-based contagion as mutually exclusive event, our empirical results have shown that they are indeed complementary, a prolong short run that eventually turns into a long run contagion, supporting Pesenti and Tille (2000) argument.

3. Data and empirical models

3.1. Data description

The daily data for exchange rate (local currency per USD, end of the period) come primarily from E-Ikon DataStream and it spans from 3rd June 2019 to 15th February 2022. The data are Malaysian ringgit (MYR), Singapore dollar (SGD), Thai baht (THB), Indonesian rupiah (IDR), and Philippine peso (PHP). The cut-off dates for pre and during crisis periods vary across countries and were obtained from Oxford Covid-19 Government Response Tracker.

Table 1
Mean and Standard Deviation of Pre and During Covid-19 Exchange Rate Volatility Indices: Daily Observations from 2019:6–2020:12.

Country	Mean	Standard Deviation	Min/Max	Kurtosis
2019:06–2020:03 (Pre)				
Indonesia	0.2870 (1)	0.1784 (1)	0.0475/ 0.9645	4.6435
Malaysia	0.2019 (4)	0.0787 (5)	0.0904/ 0.4811	2.8886
Philippines	0.2847 (2)	0.0971 (3)	0.1387/ 0.5843	0.5695
Singapore	0.1717 (5)	0.0912 (4)	0.0477/ 0.6017	8.4331
Thailand	0.2349 (3)	0.1126 (2)	0.0636/ 0.6708	2.5452
2020:03–2020:12 (During)				
Indonesia	0.4341(1)	0.2534 (1)	0.0552/ 1.6351	6.5747
Malaysia	0.2441 (3)	0.1379 (3)	0.0992/ 0.0810	6.5468
Philippines	0.2010 (4)	0.0704 (5)	0.0831/ 0.3945	−0.0700
Singapore	0.1453 (5)	0.1879 (2)	0.0016/ 0.7789	1.6856
Thailand	0.2575 (2)	0.0741 (4)	0.1144/ 0.4717	0.2142

*Notes: Number in parentheses are ranks. Source: E-IKON Datastream.

The pre-crisis period starts from 3rd June 2019 to the dates when lockdowns were announced. According to WHO (2020), lockdowns are often referred to as large scale physical distancing and non-essential movement restrictions, including stay-at-home orders which is the strictest measures possible to contain the pandemic. The earliest imposition of lockdowns among ASEAN-5 countries was in Indonesia on 17th March, followed by Malaysia on 18th March and the Philippines on 21st March. Thailand imposition was on 26th March and finally Singapore on 7th April.

3.2. Volatility measure

The volatility measure adopted in our study is constructed following Hurley and Santos (2001). The construction uses moving average sample standard deviation of the growth rate of exchange rate to capture time varying movements of exchange rate fluctuations:

$$\left[\frac{1}{12}\sum_{i=1}^{12}\left(Z_{t+i-1}-Z_{t+i-2}\right)^2\right]^{\frac{1}{2}}$$

where Z_t is the log of exchange rate. This measure is widely employed in the international trade and exchange rate volatility literature (Hurley and Santos, 2001).

As shown in Table 1, the average exchange rate volatilities have increased for Indonesia, Malaysia and Thailand during the Covid-19 but decreased for the Philippines and Singapore. Indonesia experienced the highest average and variations in volatility pre and during Covid-19, similar to the findings of Hurley and Santos (2001) during AFC while Singapore's exchange rate volatility has always been the lowest reflecting the country's strong economic fundamentals. In spite of Singapore having the lowest mean average volatility among the ASEAN countries, its exchange rate variation has increased during Covid-19 taking the second spot behind Indonesia. Moreover, the increased in kurtosis of Indonesia and Malaysia indicates the volatility of exchange rates have shifted to fatter tail distribution, whereas the significant decline in kurtosis (less than 3) of remaining nations imply lighter tail distributions in which their exchange rates volatility are more concentrated around the peak.

We also examine the exchange rate volatility correlations across the ASEAN-5 countries with the results in Table 2 show almost all the correlations across these nations volatility in exchange rates decline during Covid-19 from the period before. The above diagonal values refer to correlation of these countries exchange rate volatilities during crisis period, and the below diagonal values refer to pre-crisis period volatilities. There are high volatility correlations before the period of Covid-19 in March 2020 and for some, they are cut by more than half during Covid-19. For example, the correlation of Malaysian ringgit and Singapore dollar exchange rates volatility is 0.6950 (pre) and has declined to 0.1909 (during Covid-19). The results are in contrast to the experience during the AFC whereby ASEAN-5 correlation in exchange rate volatilities had heightened.

3.3. Empirical model I: Vector error correction (VECM)

In order to evaluate the dynamic linkages of exchange rates among these currencies both in short and long run, we adopt cointegration and vector error correction model (VECM) within the vector auto regression (VAR) framework. The initial step is to examine the stationarity or integration properties for the log of exchange rates using augmented Dicky Fuller (ADF) and Philips-Perron (PP) unit root tests for both period of pre and during Covid-19. In addition to the standard interpretation of unit root tests, the stationarity of ASEAN-5 exchange rates suggests these series are moving together against the third currency, in this case their anchor currency, U.S. dollar (Klyuev and Dao, 2016). In other words, when a currency is moving in a fairly narrow band against another currency or is pegged to another currency, then the exchange rate between these two currencies should be stationary. Furthermore, to use the VECM model, all our variables need to be I(1).

Next, in order to avoid arbitrary ordering of the variables in the triangular identification schemes used in VAR-VECM, we use variable-lag Granger causality and Transfer Entropy that was recently developed (Amornbunchornvej et al., 2019). The typical Granger causality makes a strong assumption that the effect of time series at every time point is influenced by a combination of other time series with a fixed time delay (Amornbunchornvej et al., 2019). However, this assumption of fixed time delay may not be accurate when these variables move in a non-linear manner. To address this potential problem, we attempt to use variable-lag Granger causality and Transfer Entropy that is a non-linear structural equations of Granger causality. The ordering of the ASEAN-5 countries is based on the degree of strength define by Bayesian Information Criterion (BIC) difference ratio in variable-lag Granger causality and Transfer Entropy ratio in variable-lag Transfer Entropy to determine whether X causes Y. The assumption is that the larger the strength of causation, the greater the susceptibility of that exchange rate to another exchange rate. The analysis is needed since the cointegration tests are sensitive to the inclusion or exclusion of a country's exchange rate (Majid and Kassim, 2009). The results from these tests are used in the ordering of our VAR multivariate framework and as robustness checks to our conclusion. An alternative approach in VAR ordering is using variance decomposition of each of this time series (Hurley and Santos, 2001).

From here, we construct a structure to be used as a basis in our VAR (structural VAR) pre and during the Covid-19. The structure is important when we analyse the innovation shocks and its transmission from one exchange rate to the other in order to avoid specification of relationship that are weak or may not exist. The following are estimates of VAR model:

$AY_t = \mu + \sum_i \tau_i Y_{t-i} + B\varepsilon_t$(structural VAR) (2).

$Y_t = \alpha + \sum_i Z_i Y_{t-i} + Q\varepsilon_t$(reduced form VAR) (3).

Where Y_t is a (n*1) vector of I(1) variables; β_1 are (n $\times$ n) matrices of parameters; α is a (n $\times$ 1) vector of constants; ε_t is a vector of

Table 2
Pairwise Correlation between Countries' Volatility Exchange Rates.

	MY R	IDR	PHP	THB	SGD
MYR	1	0.7498*	**0.2970**	0.3328*	0.1909
IDR	0.847*	1	**0.3909***	0.3728*	0.2282
PHP	**0.2473**	**0.3497***	1	**−0.2227**	0.2889
THB	0.7286*	0.7413*	**0.3302***	1	−0.1670
SGD	0.6950*	0.6752*	0.4763*	0.8029*	1

*Note: The above diagonal values refer to correlation of these countries during crisis period: below diagonal values refer to correlation of these countries pre-crisis period. The bold numbers show the decreased in correlation from pre to during Covid-19. However, take note that these correlations are static and not corrected for heterocedasticity biased.

error terms; and k is the maximum number of lag to obtain white noise process. The appropriate lag used is identified using Schwarz information criteria (SC) and error autocorrelation (correlogram).

To investigate the existence of a long run equilibrium relationship between these ASEAN-5 currencies, we employ the Johansen and Julius maximum-likelihood test procedure.[2] This test is based on maximum likelihood estimation (MLE) of the VAR model. This means that each variable is treated as an endogenous variable that depends on its own lags and the lags of other variables, including the exogenous variable. Specifically, Y_t is a vector of n stochastic variables, then there exists a k-lag vector autoregression with Gaussian errors of the following form:

$$\Delta Y_t = a + \Gamma_1 \Delta Y_{t-1} + ... + \Gamma_{k-1} \Delta Y_{t-k-1} + \Pi Y_{t-1} + z_t \tag{4}$$

where Γ are coefficient matrices and z_t is a vector of white noise process.

In addition to optimal lag length test within the VAR framework, we also conduct a cointegration test to provide a complementary support to the unit root conclusion. The cointegration procedure yields two likelihood ratio test statistics, referred to as the trace test and the maximum eigenvalue (λ-max) test. Engle and Granger (1987) observe that although economic time series (log of exchange rates) may not have the stationary characteristics at level, meaning that the time series can wander through time, however, the linear combination of these series can converge to a long run relationship over time. In other words, system's short-run dynamic is determined, among others, by its steady state, and hence the latter should be incorporated into the model exogenously. In the context of present analysis, a finding of cointegration not only mean that linear combination of ASEAN-5 exchange rates converge to a steady state in the long run but they move together against their anchor currency, U.S. dollar (Klyuev and Dao, 2016). So, the transmission mechanism underlying these exchange rates dynamic movement hypothesis is stable and thus more predictable over long periods. Furthermore, shocks that are unique to one time series will quickly dissipate as the variables adjust back to their common trend.

Using 3-lagged variable model, the VECM's specification is as follows:

$$\Delta Y_t = \alpha + \Pi Y_{t-1} - \Pi_1 \Delta Y_{t-1} - \Pi_2 \Delta Y_{t-2} + \varepsilon_t \tag{5}$$

Generalization of the above result yields the following expression forΔY_t:

$$\Delta Y_t = \alpha + (\sum_i^n Z_i - I) Y_{t-1} - \sum_i^{n-1} (\sum_{j=i+1}^n Z_j) \Delta Y_{t-i} + \varepsilon_t \tag{6}$$

where$\Pi = \sum_i^n Z_i - I = \eta\beta, \Pi_i = \sum_i^{n-1} \left(\sum_{j=i+1}^n Z_j \right)$, ($\eta, \beta$ are adjustment and cointegration matrices respectively[3]). From equation (6), we can summarize the conventional Error Correction Model (ECM) for cointegrated series as:

$$\Delta Y_t = \alpha_0 + \gamma Z_{t-1} + \sum_i^{n-1} \delta_i \Delta Y_{t-i} + \sum_i^{n-1} \theta_i \Delta X_{t-i} + \varepsilon_t \tag{7}$$

Z is the Error Correction Term (ECT) and is obtained from the OLS residuals from the following long-run cointegrating regression:

$$Y_t = \alpha_0 + \alpha_1 X_t + \mu_t \tag{8}$$

Z_{t-1} = ECT= $Y_{t-i} - \alpha_0 + \alpha_1 X_{t-1}$ (9).

The ECT shows how the last period deviation from the long run equilibrium (the error) influences the short run dynamic of the dependent variable. Thus, the coefficient γ measures the speed at which Y returns to equilibrium after a change in Z.

While VECM methodology provides evidence to the existence of cointegration during the pandemic, it doesn't answer the existence of contagion across these exchange rates, and which exchange rate reacts first to the Covid-19 shocks and which comes in later. In other

[2] This approach is especially appealing since it provides a unified framework for estimating and testing cointegrating relations in the context of a VECM model. Thus, by treating all the variables as endogenous, this approach avoids the arbitrary choice of the dependent variable in the cointegrating equations, as in the Engle-Granger methodology. They have also been shown to have good large- and finite-sample properties (see Phillips, 1991, Cheung and Lai, 1993).

[3] Number of long-run equilibria is exactly the rank of matrixΠ.

words, we need more specific time and frequency scale variables to dissect what happen to these exchange rates on daily basis that lead to long run effect. The latter part is proved using wavelet analysis. The wavelet approach offers time and frequency decomposition on ASEAN-5 exchange rates co-movement. The multi scale relationship is important as dynamics of co-movement of currencies can potentially be different at different time horizon (Meng and Huang, 2019). Therefore, we use wavelet power spectrum (WPS) to estimate the variation of each exchange rates movement and wavelet coherency (WC) to capture the covariance between two time series at different time and frequency domains.

3.4. Empirical model II: Wavelet analysis

The wavelet transform is a powerful tool for analyzing nonstationary time series in both time and frequency domains. It can overcome issues related to current techniques in econometrics on: (1) how these markets move together and (2) find the strength of cointegration in the Johanson cointegration method. As mentioned by Dewandaru et al. (2017) and Forbes and Rigobon, (2002), the standard correlation in econometrics fail to correct for heteroscedasticity problem that may cause over estimation of the contagion effect. Since wavelet analysis is flexible and does not require strong assumption about the data generating process and its stationarity, such problems will not arise here.

In this study, we apply wavelet power spectrum (WPS) and wavelet coherency (WC) in the form of continuous wavelet transform, following Dewandaru et al. (2017). WPS and WC capture the variation and covariation in exchange rates. The continuous wavelet transforms of a time series W_x with respect to t is a function of the following convolution:

$$W_x(\tau, s) = \int_{-\infty}^{+\infty} X(t)_{t,s}(t)dt = \frac{1}{\sqrt{s}}\int_{-\infty}^{+\infty}\left[x(t)\left(\frac{t-\tau}{s}\right)\right]dt \tag{10}$$

where the bar denotes the complex conjugate, τ is the time position/parameter controlling its location, s is the scale or dilation parameter that controls width of the wavelet, and is a normalization factor to make sure that wavelet transforms are comparable across frequency bands and time series. The chosen mother wavelet is Morlet wavelet given by:

$\varphi_{\omega_0} = \pi^{-\frac{1}{4}}$ j $\omega_0 \tau e^{-\frac{t^2}{2}}$ (11).

The Morlet wavelet is a complex sine wave within a Gaussian envelope and ω_0 is the wave number. In this study, we choose ω_0 equals to 6 since it provides a good balance between time and frequency localization (Dewandaru et al., 2017). According to Aguiar-Conraria and Soares (2011), Morlet wavelet has extra properties such as its ability to convert wavelet scales into equal frequencies; optimal joint time–frequency concentration; equal time and frequency radius and more importantly, it is an analytical wavelet. WPS is defined as:

$$(WPS)_x(\tau, s) = |W_x(\tau, s)|^2 \tag{12}$$

WPS measures the relative variance contribution at different time and frequency for each time series. The hypothesis is the statistically significant of wavelet power against the null hypothesis of a stationary process. In its output, the thick black contour estimated using Monte Carlo simulations phase randomized surrogate series defines the region that is significant at 5% statistical level against the red noise. The cone of influence (COI) signals the edge effects is displayed using grey line and any areas outside this grey line (or COI) should be neglected as there is no statistical confidence. The power of variation ranges from blue (low power) to red (high power). WC is given by two times series $x(t)$ and $y(t)$ as follows:

$$R^2_{x,y}(\tau, s) = \frac{\left|s\left(s^{-1}W_{x_ix_j}(\tau, s)\right)\right|^2}{\left(s\left(s^{-1}|W_{x_i}(\tau, s)|^2\right).s\left(s^{-1}|W_{x_j}(\tau, s)|^2\right)\right)}, R^2 \in [0, 1] \tag{13}$$

where S is a smoothing operator in time and frequency bands. The WC measures co-movement of two time series over time and frequencies. High (low) value of wavelet coherency indicates a strong (weak) co-movement, and this is displayed using contour plot. The horizontal axis represents time component, and the vertical axis represents frequency component. The degree of co-movement is measured through the coherency ranging from blue (low coherency) to red (high coherency) and regions that have high coherency shows strong local correlation. Similar to WPS, we only read the values within the cone of influence as it shows a 5% significance level estimated from a Monte Carlo simulation. In addition to the colour ranges, the appearance of arrows shows a phase-difference, meaning the co-movement of these time series at the specified frequency. If $\varnothing_{xy} \in \left[0, \frac{\pi}{2}\right]$, then the two series x and y are said to move in-phase with x leads y; if $\varnothing_{xy} \in \left[-\frac{\pi}{2}, 0\right]$, then y leads x. The two series move anti-phase when $\varnothing_{xy} \in \left[\frac{\pi}{2}, \pi\right]$ with y leading, or $\varnothing_{xy} \in \left[-\frac{\pi}{2}, -\pi\right]$ with x leading. Therefore, the WC has the power to not only show exchange rate co-movements during the pandemic at different time and frequency but offers the leading market that can has spill over effect to other market.

In this study, we define a short-term horizon as less than 32 days (or higher frequency band up to 2ˆ5 = 32 working days) to reflect the trading behaviour of short- and medium-term investors while beyond this period is considered as long term or lower frequency bands. Meng and Huang (2019) study on Asian effective exchange rates define short term as 2–8 days, medium term as 8–32 days and long term as 32–64 days. Bodart and Candelon (2000) have also used 2–3 days period for high frequency. They followed Baig and Goldfajn (1999) study during AFC that the impact on neighbouring markets of shocks originating from Thailand's stock market disappeared after 4 days. Hence, pure contagion effect that falls in short term period are associated with market sentiment, liquidity preferences, cross-border asset listing, financial panics, herd behaviour, loss of confidence and increased risk aversion (Dewandaru et al., 2017). In contrast, the lower frequency of more than 32 working days (1 month) reflects the fundamental linkages that are related to real economy and long run equilibrium among ASEAN-5 exchange rates.

4. Results and analysis

The ADF and PP tests show that all series are stationary after first differencing, implying that they are integrated of order one, I(1)[4]. The unit root tests are not satisfactory at level implying that at level, the exchange rates can wander off from its long run trajectory and do not have any specific level targeting towards the U.S. dollar[5]. Since these exchange rates are I(1), the statistical attributes of these exchange rates such as mean and variance are constant after first differencing.

Next, from the variable-lag Granger Causality and Transfer Entropy results, we conclude that the number of bidirectional causations decrease from pre-pandemic period to during Covid-19 period. In other words, we have more unidirectional effects among ASEAN-5 countries during the pandemic that results in absorbing or isolated states in which such effect remains in that particular state and doesn't spill over to its neighbouring countries. According to Pesenti and Tille (2000), the international transmission of a currency crisis can occur even if country A and country B do no trade with each other but the exports are competing in the same foreign markets. Since the causation between these countries are reduced during the pandemic, it is more likely that the synchronised movement in their exchange rates are due to the third currency, U.S. dollar (Klyuev and Dao, 2016). Based on BIC and Transfer Entropy ratios, the ordering of variables in our structured VAR model during both periods starting with the most volatile exchange rate are as follow:

Indonesia -> Thailand -> Singapore -> Malaysia -> Philippines. (Pre and During).

Next, the trace test and the maximum eigenvalue (λ-max) test for cointegration postulate the existence of one cointegrating vector ($r = 1$) in each period. This means there is a common factor or permanent component i.e. the U.S. dollar driving the entire system of exchange rate movements in ASEAN-5. These variables are connected in the long run and their eccentricities from the long run equilibrium have been rectified.

Given the cointegration results, the next stage in our model building process requires the construction of a multivariate VECM where the time series are found to be cointegrated. Looking at the long run results in Equation (14) and (15) below, there seem to be a positive relationship between Indonesian rupiah and Singapore dollar and negative relationship between currency pairs of Indonesian rupiah and Malaysian ringgit and Indonesian rupiah and Thai baht in both periods. The positive relationship between Indonesian rupiah and the Philippine peso before the pandemic turns into negative relationship during the pandemic. These results do not mean that the countries are following the action of their neighbours, but in our opinion, more of the reaction towards the anchor currency, US dollar.

The positive relationship here implies that the two exchange rates reaction to the common shocks move up and down in a broadly synchronous fashion but a negative relationship implies the asynchronous movements in the two exchange rates. If we take an example of Singapore dollar and Indonesian rupiah, this implies that a 1% change in Singapore dollar moves with 1.03% change in Indonesian rupiah (pre-pandemic) while the effect is 8.75% during the pandemic[6]. For exchange rates of Singapore, the Philippines and Thailand, the long run impact with Indonesia exchange rate amplifies during this Covid-19. In contrast, the elasticity of Indonesian rupiah and Malaysian ringgit becomes insignificant and decline during the pandemic.

Pre Covid-19 Results:

$IDR_{t-1} = (1.03^{***})*SGD_{t-1} - (2.73^{***})*MYR_{t-1} + (0.04)*PHP_{t-1} - (0.64^{***})*THB_{t-1} - 3.93$ [2.85] [-8.16] [0.18] [-3.43] (14).

LM (2) = 17.45 (0.8648***) LM (4) = 29.58 (0.2401***).

During Covid-19 Results:

$IDR_{t-1} = (8.75^{***})*SGD_{t-1} - (1.16)*MYR_{t-1} - (4.93^{***})*PHP_{t-1} - (3.72^{***})*THB_{t-1} - 21.29$ [1.88] [1.18] [1.07] [0.52] (15).

LM (2) = 28.75 (0.2744***) LM (4) = 35.05 (0.0874).

*, ** and *** denote significance at 1%, 5% and 10% respectively. The values in square parentheses are t-statistics.

Next, we analyse the magnitude and speed of adjustments among these countries exchange rates from their long run equilibrium pre and during Covid-19 through the ECTs in Table 3. First, the magnitude of ECTs pre COVID-19 are almost negligible across ASEAN-5 and should there be any shocks to the equilibrium, only Indonesian rupiah that is statistically significant in bringing the exchange rate back to its long run path by 8.42% adjustment daily. The speed of adjustments back to this long run equilibrium is about 21 trading days (8.42%*254 days = 21 trading days).

In contrast, during the Covid-19 period, Indonesia, Malaysia and Singapore ECTs are all significant in bringing their exchange rates back to their long run equilibrium. In other words, when there is any disequilibrium during this pandemic period, 6.58%, 1.47% and 2.45% of short run adjustments to a long run equilibrium respectively come from Indonesian rupiah, Malaysian ringgit and Singapore dollar. These adjustments to long run convergence take up to 21 days for Indonesian rupiah, 68 days for Malaysian ringgit and 40 days for Singapore dollar. The central banks of these three countries would intervene in the market to stabilise any excessive fluctuations in their exchange rates at the mentioned ECTs to avoid prolonged contagion effect[7].

Although the VECM results are useful in proving to us the existence of a long run contagion effect and the daily adjustments when there is disequilibrium, the short run results between these exchange rates are inconclusive. The wavelet power spectrum results (from

[4] The results for Augmented Dickey Fuller (ADF) and Philips Perron (PP) unit root tests, variable-lag Granger Causality and variable lag Transfer Entropy, trace test and maximum eigen value test are available upon request.

[5] The ADF and PP tests results are available upon request.

[6] The coefficient represents the elasticity since we have log–log regression.

[7] The VECM short run results are available upon request.

Table 3
Error Correction Term (ECT) for ASEAN-5 Currencies.

Dependent Variable	Pre-Crisis Period (ECT)	During Crisis (ECT)
IDR	−0.0842***	−0.0658***
MYR	0.0039	−0.0147***
PHP	0.0177	−0.0051
SGD	0.0170	−0.0245***
THB	0.0013	0.0139

*The ECT shows the daily percentage of adjustments to bring the ASEAN-5 currencies back to its long run equilibrium. During the crisis period, the daily rate of adjustment for Indonesian rupiah, Malaysian ringgit and Singapore dollar are 6.58%, 1.47% and 2.45%.

Table 4
Wavelet Power Spectrum (WPS) for ASEAN-5 Currencies.

Countries	Type of volatility (when frequency less than 32 days)	Type of volatility (when frequency more than 32 days)	Period of high volatility
Indonesia	High	High	October 2019 to July 2020
Malaysia	High	High	October 2019 to July 2020
Singapore	High	High	October 2019 to July 2020
Philippines	Mild	–	February 2020 to April 2020
Thailand	Mild	High	October 2019 to July 2020

*From the wavelet power spectrum, the formation of blue areas represents low volatility, the orange areas represent mild volatility, and the red areas represent high volatility. In the case of Indonesia, high volatility was evidenced in both periods of less and more than 32 days. These high volatilities lasted from October 2019 to July 2020.

Appendix 1) are summarised in Table 4. WPS shows the evolution of variance for all exchange rates over the entire observations across different time, coherence and frequency. The lockdown dates were announced in March 2020, but for countries like Indonesia, Malaysia, and Singapore, the high-power areas that represent heightened volatility (red colour) have shown since October 2019 and lasted until July 2020. On the other hand, Philippine peso only experiences mild volatility at the start of lockdown and subsides two months later. For Thai baht that starts out with mild volatility at high frequency band of less than 32 turns into high volatility at low frequency band. According to Pesenti and Tille (2000), self-fulfilling prophecy from second generation currency model can shift market participants' expectations in the short run to one that plays a prominent role in the determination of a crisis in the long run. Combining with the results from VECM (Table 4) that cointegration exists, we know that should there be any disequilibrium, the central banks will intervene to stabilize the volatilities in order to prevent disruption to long run equilibrium.

To determine the lead and lag currency, we use wavelet coherency (Appendix 2) that provides evaluation on market integration. The results are summarized in Table 5. The WC shows a country that first response to the Covid-19 shocks followed subsequently by another country. In March 2020 (at x-axis of 200), currency pairs of Indonesian rupiah-Thai baht and Indonesian rupiah-Malaysian ringgit show high coherency areas (red colour) both in the short run (high frequency band) and long run (low frequency band). High coherency areas represent high degree of co-movement derived from coefficient correlation. By definition, contagion is a permanent shift in correlation during the crisis period. Hence, the results suggest pure contagion due to market sentiments in the short run that spills over to fundamental-based contagion in the long run for these two currency pairs. In the case of Indonesian rupiah-Singapore dollar, and Indonesian rupiah-Philippine peso, the high coherency areas only appear temporarily in the short run without any long run effect.

It is also interesting to note on the co-movement of Malaysian ringgit and Singapore dollar that seems to have no effect on each other in the short run but in the long run, Malaysian ringgit will react first followed by Singapore dollar. It is to be noted that Malaysia is Singapore's third largest trading partner and both countries main exports are the U.S. and China. In the case of Malaysian ringgit-Thai baht, we find the leading role of Malaysia in the short and long run. There was a temporary high coherence area at the start of the pandemic for currency pair Malaysian ringgit and the Philippine peso but this pair is largely dominated by low coherency areas (blue colours). For Thai baht and Singapore dollar, the lead in the short run comes from Singapore dollar performance but in the long run it depends on Thai baht. The Philippine peso lag all other currencies in both short and long run period.

In addition to the co-movement of these currency pairs, we extended the analysis to include the possibility of contagion from China

Table 5
Wavelet Coherency for ASEAN-5 Currencies.

Currency Pairs	Short Run Lead (Degree of Coherency)	Long Run Lead (Degree of Coherency)
Indonesia and Malaysia	Indonesia (High)	Indonesia (High)
Indonesia and Philippines	Indonesia (High)	- (Low)
Indonesia and Thailand	Indonesia (High)	Indonesia (High)
Indonesia and Singapore	Indonesia (High)	- (Mild)
Malaysia and Philippines	Malaysia (High)	- (Low)
Malaysia and Thailand	Malaysia (High)	Malaysia (High)
Malaysia and Singapore	- (High)	Malaysia (High)
Philippines and Thailand	Thailand (Mild)	- (Low)
Philippines and Singapore	Singapore (Mild)	- (Low)
Thailand and Singapore	Singapore (High)	Thailand (High)

*The table shows the leading currency in the short and long-run period. For example, the currency pair of Indonesia and Malaysia shows the co-movement in both periods are led by Indonesian rupiah. The bracket shows the degree of coherence with 'high' implies high degree of correlation which is visible from the red patch in the graph.

and Japan, the region first and fourth largest trading partners (UN Comtrade). The results (Table 6) show statistically significant co-movement in the short run but not in the long run, with exception to the Philippines and China. China has managed floating exchange rate regime while Japan adopts free floating exchange rate.

5. Robustness testing

To check the robustness of our findings, we use variance decomposition method following Hurley and Santos (2010) and Lee and Azali (2010). The results (Table 7) show that in the short run, the variation in Indonesian rupiah comes entirely from itself without contribution from any currency. This supports the WC results that when all the currencies are paired with Indonesian rupiah, the co-movement is always led by Indonesia rupiah in the short run not to mention that Indonesian rupiah is the most volatile currency in the region. The variance decomposition for the Philippines peso is dominated by its own movement which supports the WC results that there are no other leading currencies to peso in the long run. Overall, the variance decomposition shows that a variation in a particular currency does not only depend on its own movement, but its variability is also explained by movement in other currencies which suggest the possibility of currency market contagion in short and long run period during the Covid-19 crisis.

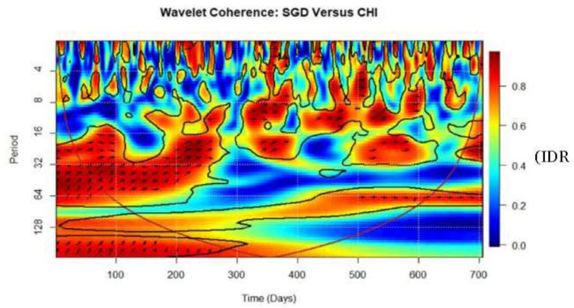
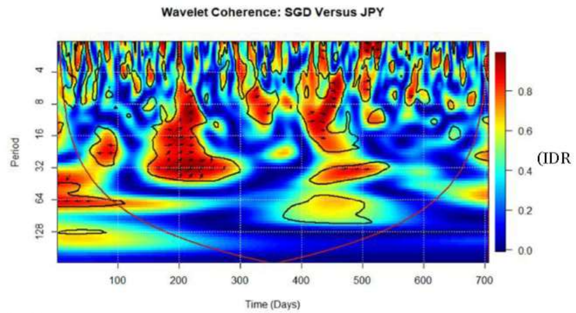
6. Policy conclusion

We started this paper with two main objectives: (1) to investigate the existence of contagion effect in ASEAN-5 exchange rates during Covid-19 (2) the nature of contagion whether it is a pure-contagion (short run) or fundamentals-based contagion (long run) or both are complementary in nature. To begin with, the ADF and PP unit root tests show non–stationarity at log level of exchange rates. This implies that ASEAN-5 exchange rates do not oscillate in a specific bandwidth or have any specific target of U.S. dollar to maintain which is consistent with the free floating of Indonesian rupiah, the Philippines peso and Thai baht while Malaysian ringgit and Singapore dollar are classified as managed floating. However, the unit root tests are stationary at first differencing, which suggests that the fluctuations in the exchange rates growth are monitored and as often acknowledge by central banks, they will intervene to dampen any excessive volatility of their exchange rates vis-à-vis U.S. dollar (Klyuev and Dao, 2016). To decide on the ordering of the variables in the VAR-VECM framework, we use the variable lag Granger causality and Transfer Entropy that show the number of bidirectional causations decrease from pre-pandemic to during Covid-19 period. This intuitively suggests that if co-movement exists among ASEAN-5 exchange rates during the pandemic, they could potentially be due to the anchor currency, US dollar and not neighbouring countries effect. For example, it is unlikely that Central Bank of Malaysia manages ringgit based on the movement of Thai baht or the Philippines peso but more likely so due to its volatility against US dollar.

Since all the exchange rates are I(1), the VECM results demonstrate the existence of a long run equilibrium among these ASEAN-5 exchange rates. In other words, cointegration exists. Hence, any disequilibrium from the long run trajectory during this pandemic period will cause Indonesian rupiah, Malaysian ringgit and Singapore dollar to adjust on daily basis by 6.58%, 1.47% and 2.45% respectively to bring the exchange rates back to its long run equilibrium. These daily adjustments can take up to 21 days for Indonesian rupiah, 68 days for Malaysian ringgit and 40 days for Singapore dollar to converge back to its long run equilibrium.

Next, the findings from wavelet power spectrum (WPS) imply that Indonesia, Malaysia and Singapore experience high degree of exchange rates volatility throughout the pandemic period. Thailand experiences mild volatility in the short run (at frequency band of less than 32) and high volatility in the long run (at frequency band more than 32). Only Philippines that experiences mild volatility in

Table 6
Wavelet Coherency for ASEAN-5 Currencies with China and Japan.

Countries	China Short Run (China Lead)	Long Run (China Lead)	Japan Short Run (Japan Lead)	Long Run (Japan Lead)
Indonesia	 (IDR leads)	–	 (IDR leads)	–
Malaysia	✓	–	✓	–
Philippines	✓	✓	–	–
Singapore	✓	–	✓	–
Thailand	✓	–	–	–

*The ✓ shows high coherence areas are evidenced between ASEAN currencies, China, and Japan at the start of the lockdowns in March 2020. High coherence areas imply high co-movement between the currency pairs, and this is represented by coefficient correlation. With exception to Indonesian rupiah that leads the co-movement in the short run, the rest currency pairs are led by China and Japan. There is no evidence that Chinese yuan and Japanese yen can statistically influence the co-movement of ASEAN-5 in the long run except for Chinese yuan-Philippine peso pair.

Table 7
Variance Decomposition Results for ASEAN-5 Currencies.

Countries	Variance Decompositions at Lag- 1 (%)	Variance Decomposition at Lag- 32 (%)
Indonesia	Indonesia (100%)	Indonesia (37%)Malaysia (18% Philippines (18%)Singapore (17%)Thailand (10%)
Malaysia	Malaysia (69%)Indonesia (14%)	Singapore (42%)Thailand (31%)Malaysia (26%)
Philippines	Philippines (81%)Thailand (11%)	Philippines (58%)Thailand (19%)
Singapore	Singapore (66%)Thailand (27%)	Singapore (56%)Thailand (30%)
Thailand	Thailand (70%)	Thailand (70%)Singapore (23%)

the short run and long run volatility subsides.

The wavelet coherency (WC) shows Indonesian rupiah reacts first to the Covid-19 shock in the short run followed by the remaining four countries. This is not surprising as Indonesian rupiah is the most volatile currency and it can lead to fundamentals-based contagion to Malaysia and Thailand, and temporary pure contagion based on sentimental to the Philippines and Singapore. The long run effects on Malaysia and Thailand will eventually affect Singapore's fundamentals too. Only the Philippines peso that insulates itself from the long run shocks to the other four exchange rates.

In addition, we extended our study to include China and Japan, the largest and fourth largest trading partners of ASEAN. While the degree of co-movement with Chinese yuan and Japanese yen heightened in the short run when lockdowns were imposed, there was no statistically significant long run co-movement. The robustness check using variance decomposition shows the variation of exchange rate is explained significantly by other exchange rates with exception to Indonesia (in the short run) and Philippines (in the long run).

Our findings show that ASEAN-5 central banks do intervene in their forex market to dampen excessive variation of the growth in exchange rates fluctuations from its anchor currency, U.S. dollar due to adverse impact of Covid-19. This costly intervention could mean a substantial depletion of their international reserves at a very quick rate. Hence, in the short run, it is important to manage market sentiments since prolonged negative market expectations can spill over to long run and threaten the economic fundamentals of a country that perhaps are already weaken. The short run contagion should not be undermined as self-fulfilling prophecy could mean that it leads to the long run contagion. Financial integration either through multilateral or bilateral currency swap can be arranged among these countries to hedge against exchange rate risk and potential short selling from speculators.

In the long run, the fundamentals-based contagion requires these countries to diversify their trading partners and reform the structure of country's fundamentals including its current account balance, fiscal deficit, technological growth, labour market, human development capacity and physical infrastructure. Further research is needed to identify the cause of this contagion to provide a more comprehensive narrative to these findings.

Declaration of Competing Interest

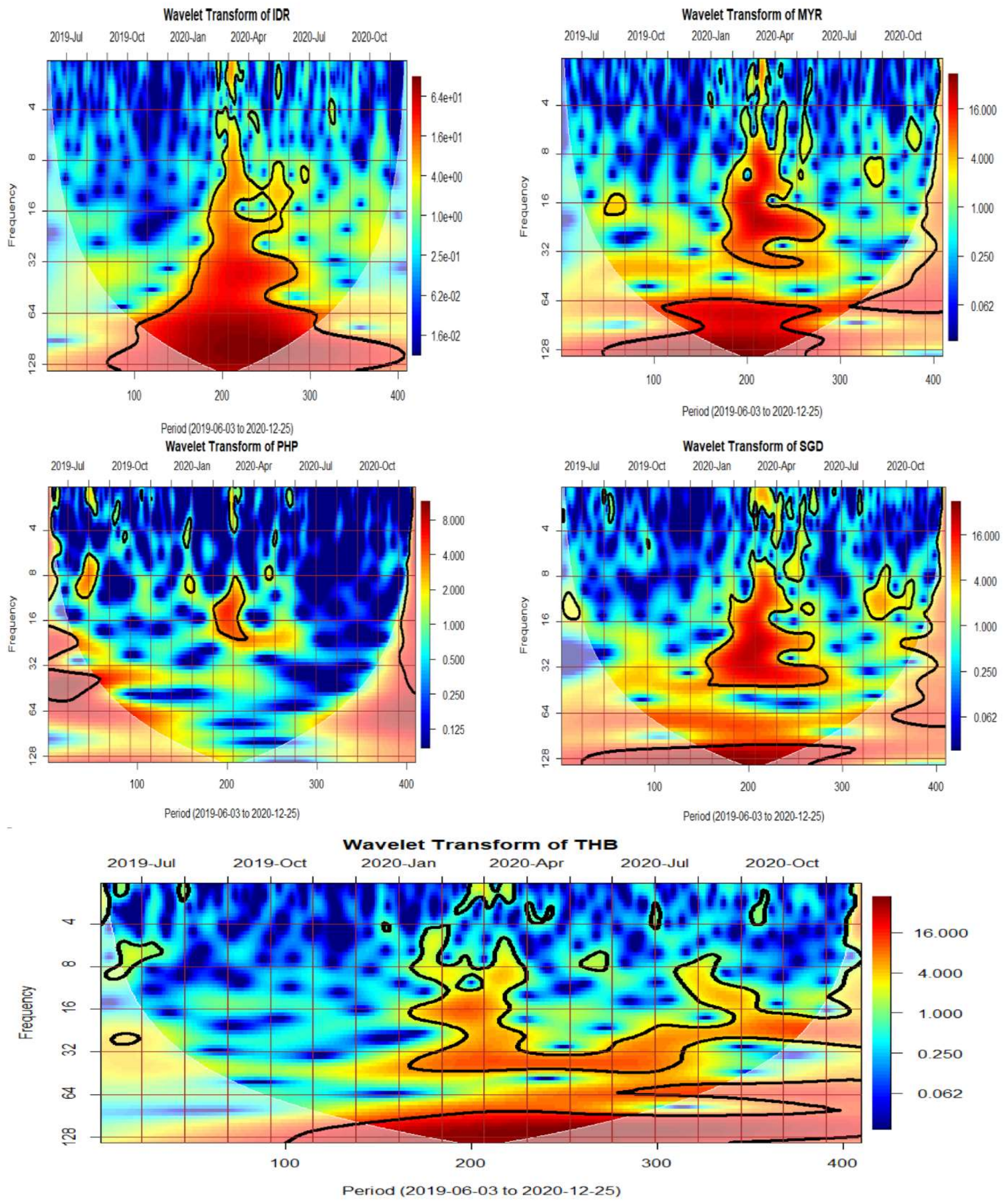
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix 1

Wavelet power spectrum (Variance) for ASEAN-5 across time and frequency domain

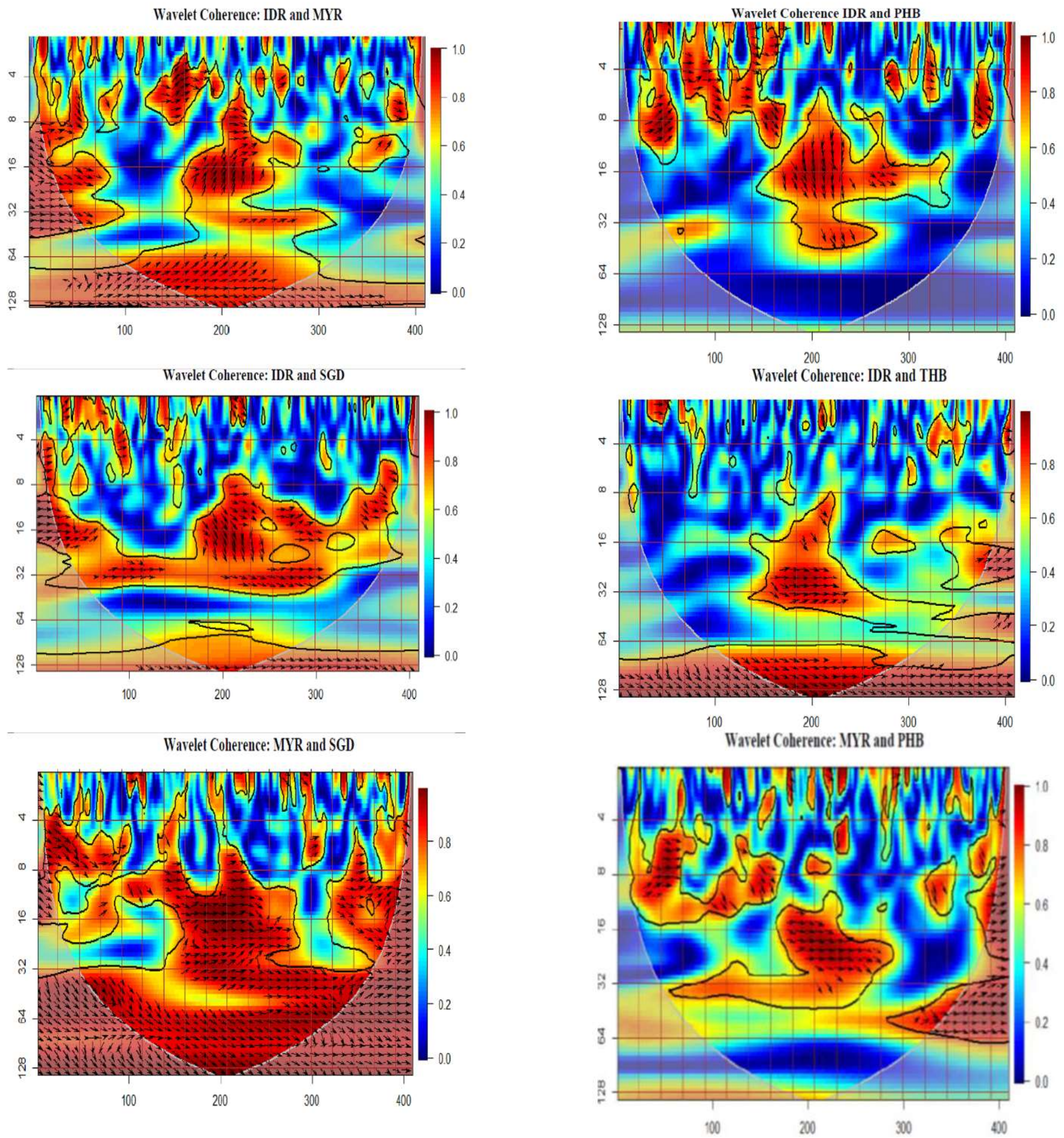


These images show heightened exchange rate volatility (red colour) during the Covid-19 period (at x-axis = 200) that exists for both short (less than 32 days) and long run period in Indonesia, Malaysia and Singapore. In contrast, the exchange rate volatility effect in the Philippines is very minimal in the short run and doesn't prolong to long run (orange patch that appears at lower frequency band). For

Thailand, it also experiences minimal volatility effect in the short run but heightened volatility in the long run.

Appendix 2

Wavelet coherence (Covariance) for ASEAN-5 across time and frequency domain



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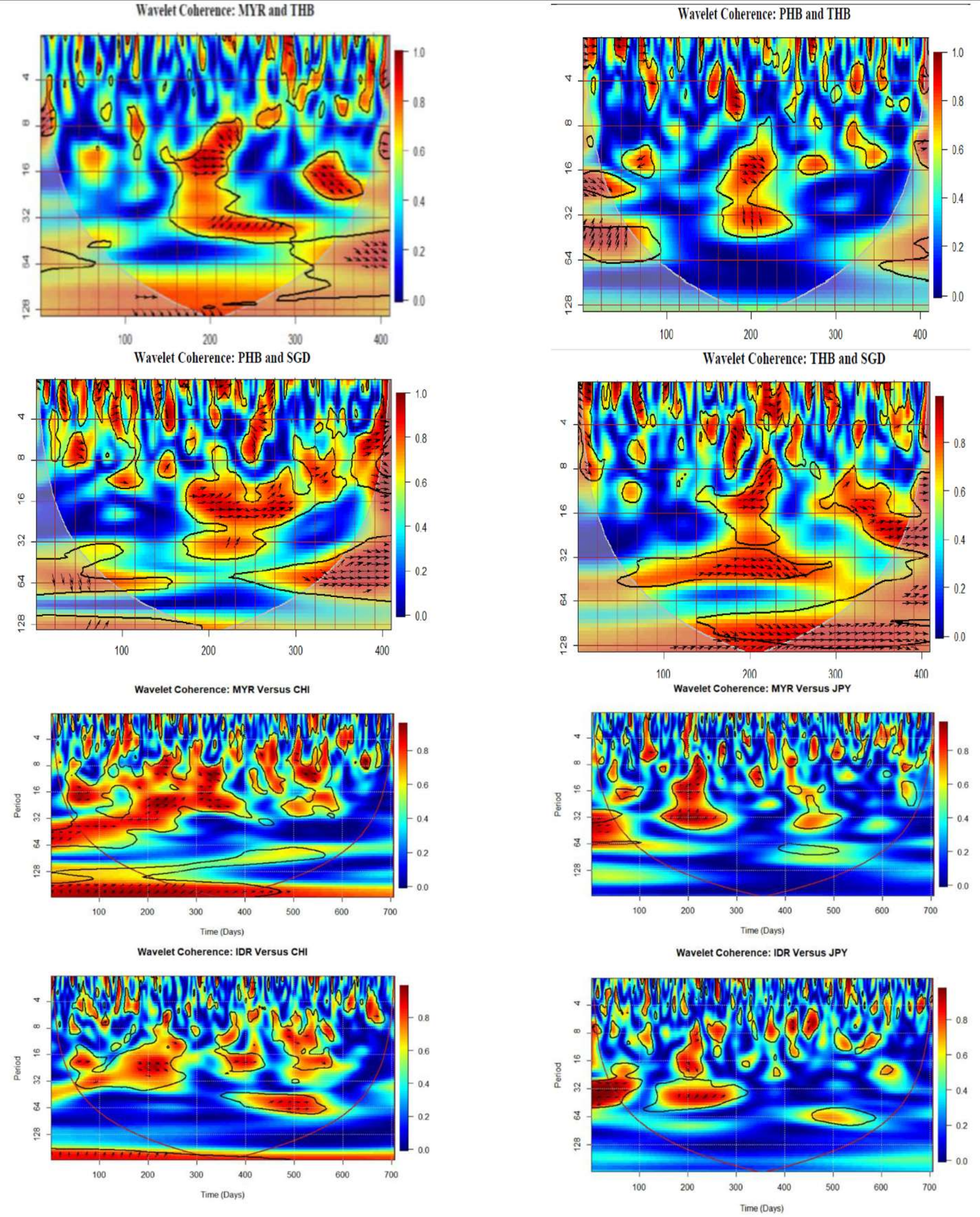

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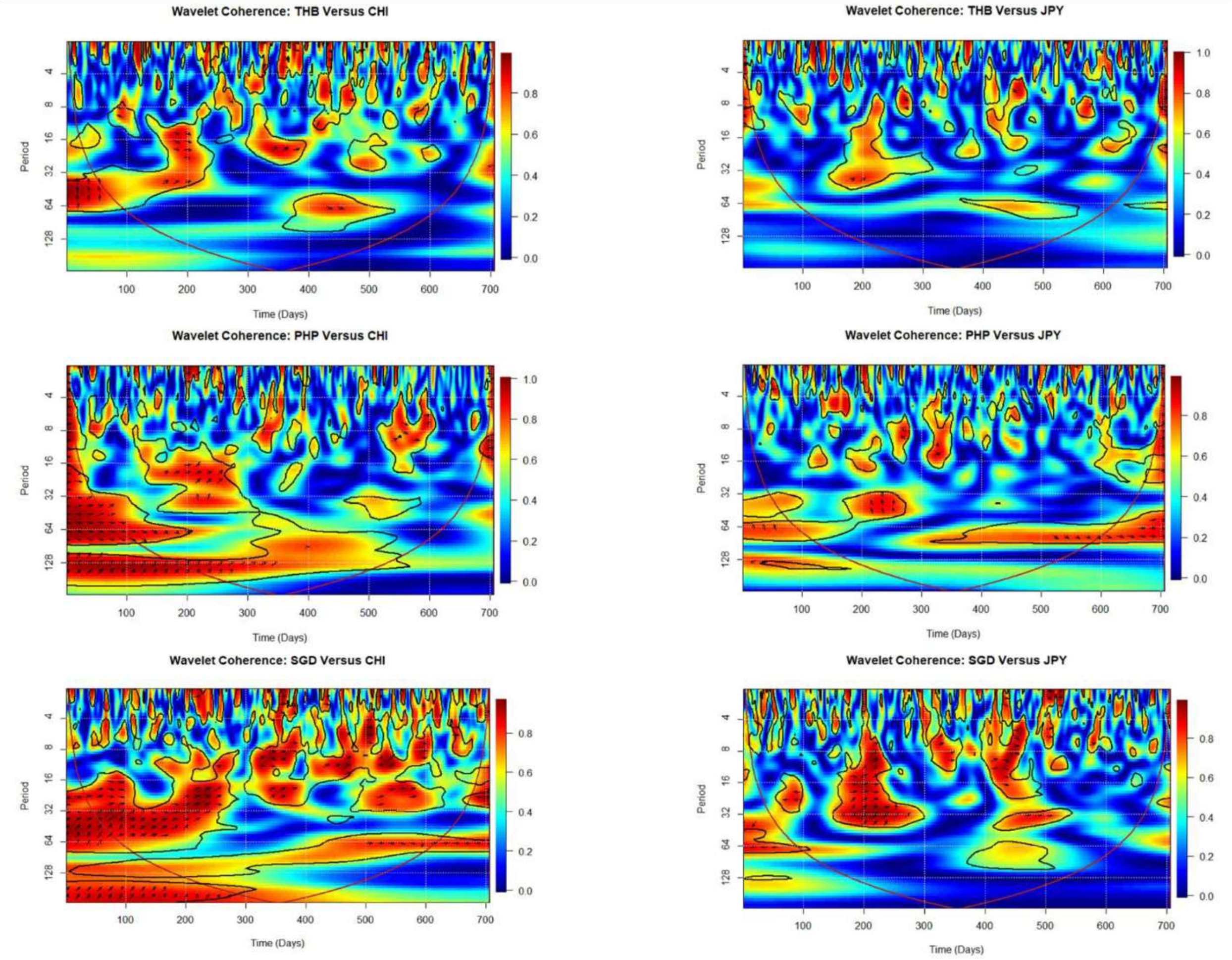

*MYR = Malaysia, IDR = Indonesia, PHP = Philippines, THB = Thailand, SGD = Singapore, JPY = Japan, CHN = China.Wavelet coherence shows the covariance of the two exchange rates across different time and frequency. The degree of co-movement is measured through the coherency ranging from blue (low coherency) to red (high coherency) and regions that have high coherency shows strong local correlation. In addition to the colour ranges, the appearance of arrows shows a phase-difference, meaning the co-movement of these time series at the specified frequency. If $\varnothing_{xy} \in \left[0, \frac{\pi}{2}\right]$, then the two series x and y are said to move in-phase with x leads y; if $\varnothing_{xy} \in \left[-\frac{\pi}{2}, 0\right]$, then y leads x. The two series move anti-phase when $\varnothing_{xy} \in \left[\frac{\pi}{2}, \pi\right]$ with y leading, or $\varnothing_{xy} \in \left[-\frac{\pi}{2}, -\pi\right]$ with x leading.

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