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Working Paper Event-Driven Changes in Volatility Connectedness in Global Forex Markets

CESifo Working Paper, No. 11606

Provided in Cooperation with: Ifo Institute – Leibniz Institute for Economic Research at the University of Munich

Suggested Citation: Albrecht, Peter; Kočenda, Evžen (2025) : Event-Driven Changes in Volatility Connectedness in Global Forex Markets, CESifo Working Paper, No. 11606, CESifo GmbH, Munich

This Version is available at: https://hdl.handle.net/10419/314645

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Impressum:

CESifo Working Papers ISSN 2364-1428 (electronic version) Publisher and distributor: Munich Society for the Promotion of Economic Research - CESifo GmbH The international platform of Ludwigs-Maximilians University's Center for Economic Studies and the ifo Institute Poschingerstr. 5, 81679 Munich, Germany Telephone +49 (0)89 2180-2740, Telefax +49 (0)89 2180-17845, email office@cesifo.de Editor: Clemens Fuest https://www.cesifo.org/en/wp An electronic version of the paper may be downloaded • from the SSRN website: www.SSRN.com

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Event-Driven Changes in Volatility Connectedness in Global Forex Markets

Abstract

Using novel methods, we comprehensively analyze volatility connectedness among most traded currencies using high-frequency data from 2009 to 2023. Our study presents the first empirical evidence of a statistically significant association between increases in connectedness and endogenously selected impactful events for most traded currencies. Moreover, we uncover the previously unexplored relationship between twenty-three events affecting global forex connectedness up to one business month ahead and further analyze pre-event connectedness changes. We also distinguish between the transitory and permanent impacts of events on connectedness and confirm the association of four events with a permanent shift in connectedness; two events are associated with the EU and US debt crises. We compute the portfolio weights and hedge ratios for portfolio optimization and uncover the Swiss franc and Japanese yen as the most suitable tools for managing currency risk. The effects of intra-day currency depreciation versus appreciation against the U.S. dollar differ significantly, but the extent of asymmetries declines over time.

JEL-Codes: C580, F310, F650, G010, G150.

Keywords: volatility connectedness, global currencies, bootstrap-after-bootstrap procedure, transitory and permanent effects, debt crisis, portfolio composition and hedging, uncertainty.

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We are grateful for the comments we received from Daniel Bartušek, František Čech, Svatopluk Kapounek, Michala Moravcová, Viet Nguyen, an anonymous referee, and conference presentation participants in Banská Bystrica, Praha, and Rethymno. The research support from the Czech Science Foundation via grant No. 22-34451S is duly acknowledged. The usual disclaimer applies.

Declarations of competing interest: none.

1. Introduction

The analysis of volatility propagation in the aftermath of the Global Financial Crisis has garnered substantial attention within the academic literature, with a particular focus on understanding connectedness in currency markets (Baruník et al., 2017; Bostanci and Yilmaz, 2020; Huynh et al., 2020). It is widely recognized that economic or political shocks play a crucial role in triggering a surge in financial connectedness (Diebold and Yilmaz, 2012; Greenwood-Nimmo et al., 2016; Chuliá et al., 2018). The phenomenon is often driven by key factors such as portfolio rebalancing (Camanho et al., 2022) and increased risk aversion (Tran, 2019), as extensively discussed in scholarly discourse.

Despite considerable interest, empirical literature lacks several key insights, and this void motivates our analysis. First, previous studies have linked increases in the forex connectedness index to economic and political shocks based on changes that were identified through simple visual inspection of the plotted connectedness (e.g., Antonakakis, 2012; Grobys, 2015; Khalifa et al., 2016; Uluceviz and Yilmaz, 2020). However, no study has yet provided statistical evidence to confirm whether these shocks are genuinely associated with amplified levels of the connectedness index. Additionally, while prior studies have demonstrated the impact of changes in connectedness on the economy (e.g., Dell'Ariccia, 1999; Ajao, 2015; Killicarslan, 2018; Kim and Lee, 2023), it remains unclear whether changes in connectedness are lagged with respect to the occurrence of shocks as well as whether shocks indeed drive these changes. Without identifying the specific leading indicator, defining the implications for portfolio management is not feasible since practical recommendations for portfolio management hinge upon the presence of a sufficiently long-delayed period, enabling investors to hedge or diversify their portfolios effectively. Further, the literature also lacks evidence about shocks' transitory and permanent impacts on global forex connectedness. Such identification is crucial, as persistent connectedness is associated with systematic shocks (Baruník and Ellington, 2024). In addition, the previous literature on forex markets (Baruník et al., 2017; Chuliá et al., 2018) has suggested differentiated impacts of shocks on connectedness coming from currencies' depreciation versus appreciation. While theoretically, any country can fight excessive currency appreciation, the constraints imposed by international reserves limit central bank actions against depreciation. This distinction is fundamental when analyzing risks in currency markets and volatility transmission among currencies. For that, it is also important to analyze asymmetries in connectedness.

Quantitative assessment of all issues discussed above is desirable because understanding the dynamics of forex volatility transmission is crucial for portfolio management, as it significantly impacts strategies related to currency hedging (Jayasinghe and Tsui, 2008; Kočenda and Moravcová, 2019). These unresolved issues serve as strong motivations for our detailed investigation. By comprehensively analyzing the above issues, our study makes a valuable contribution to the existing forex literature, effectively addressing a substantial gap in scholarly knowledge.

In our study, we proceed in two key steps. First, we utilize the bootstrap-after-bootstrap testing procedure introduced by Greenwood-Nimmo et al. (2024) to identify critical dates characterized by substantial rises in the connectedness index. By employing this approach, we endogenously determine the dates associated with notable increases in connectedness. Subsequently, we identify twenty-three events (referred to as shocks) stemming from economic, geopolitical, and natural backgrounds that have impacted the currencies' economies under analysis and received media coverage on those particular dates. To analyze the response, we examine the immediate reaction on the event day, as well as the following day, and further assess the response five, ten, and twenty-two days (equivalent to one business month) after the event. Furthermore, we complement these findings by showing that uncertainty and liquidity are essential drivers of volatility connectedness. Moreover, we further employ the recent testing procedure of Greenwood-Nimmo et al. (2024) and analyze shifts in connectedness driven by potential changes in expectations before key events. Such analysis is the first use of this method aimed at detecting shifts in volatility propagation before an event occurs. Given the critical role of expectations (Bhargava and Brooks, 2002; Lieb and Schuffels, 2022), we contend that identifying these changes in portfolio allocations ahead of announcements presents a significant challenge.

Second, having identified the events that have affected connectedness and delay lengths, we analyze the persistence of their impact on global currencies over the past fifteen years. To do so, we employ a method developed by Baruník and Ellington (2024) originally designed to differentiate between transitory and permanent impacts of shocks on connectedness among stocks. Adapting this method to the forex market, we uncover substantial changes in the persistence of connectedness, particularly during periods of economic distress. We find four events that permanently changed the transmission effects; out of these, two events are associated with the EU and US debt crises. Further, we confirm the transitory impact on the connectedness of all twenty-three events. Such a finding is particularly significant, as permanent connectedness is tied to systematic risk (Baruník and Ellington, 2024), and our study

is the first to identify these changes in the forex market. Then, we take it one step further and use these four events to define sub-periods for computing hedging ratios and portfolio weights. Following the approach of Kočenda and Moravcová (2019), we identify the optimal weights in portfolios during specific sub-periods bordered by the most impactful events, as this was not done before for most traded currencies. Finally, we adopt the approach of Baruník et al. (2017) and account for asymmetries in volatility propagation. We find that currencies' depreciation spillovers prevail over appreciation ones, but over time, such asymmetries decline by about ten percent.

Our research has substantial relevance for investors whose portfolios are denominated in most traded currencies, as we provide a comprehensive assessment that statistically identifies the impact of twenty-three endogenously selected events on volatility connectedness over the past fifteen years. Additionally, we delve into the structure of the relationship, finding that all examined events are a leading indicator of the peak of connectedness within one business month ahead. We argue that these changes stem from investors re-allocating their portfolios as shocks increase uncertainty about the future revaluation of their investments. Each of the identified events increased the volatility connectedness by 20 % or more, which highlights the importance of the findings, particularly in the context that connectedness affects hedging (Garcia and Tsafack, 2011; Feunou and Okou, 2019; Kočenda and Moravcová, 2024). We also identified four shocks that permanently affected forex connectedness. These events include shocks not yet fully assessed, as we cover the period from September 2009 until April 2023. We use data with a one-minute frequency.

The remainder of this paper is structured as follows: Section 2 provides a literature review on volatility connectedness with an emphasis on the forex market, Section 3 explains the data specifics and methods employed, and Section 4 details the obtained results and their interpretations, including the robustness test of our findings. Finally, in Section 5, we draw conclusions based on the obtained results.

2. Literature review

It has long been recognized that risk transmission originates from heightened market uncertainty (Hicks, 1931). During turbulent periods, individuals may be inclined to mitigate potential risks caused by reduced forecasting ability. During times characterized by economic and political uncertainty, investments become more speculative, and objective fundamental variables become less reliable in explaining exchange rate dynamics (Hodrick, 1989). The lack of predictability can prompt investors to re-allocate assets denominated in foreign currencies to hedge against exchange rate risk. Hedging in this context increases volatility (Wu, 2001) and currency connectedness as a consequence (Balcilar et al., 2023).

The issue is crucial, as the dynamics of connectedness affect real economic variables such as foreign direct investment (Ajao, 2015), inflation (Killicarslan, 2018), and the trade balance (Dell'Ariccia, 1999). Negative shocks tend to exacerbate these effects as investors become more loss-averse, as suggested by Bartsch (2019) and Liming et al. (2020). Information about the direction and extent of spillovers, including the delay between transmission of turmoil to currency dynamics, is helpful for policymakers as, for example, the main goal of central banks is to strengthen currency (and consequently price) stability.

In a study of the Swiss and German economies from 1999 to 2017, Uluceviz and Yilmaz (2020) identified significant volatility connectedness among exchange rates, stocks, and bonds. The study highlights the importance of considering such transmissions when diversifying portfolios. Similar effects have been observed by Diebold and Yilmaz (2009) among seven developed and twelve developing countries during crises and distress from 1992 to 2007. Other studies have also identified volatility connectedness between foreign currencies (Antonakakis, 2012; Diebold and Yilmaz, 2014; Khalifa et al., 2016). Moreover, Greenwood-Nimmo et al. (2016) concluded for G10 currencies that volatility transmission occurs mainly during economic turbulence. Studies on foreign exchange connectedness, such as Antonakakis (2012), Grobys (2015), and Chuliá et al. (2018), Chen and Schienle (2024), have reported similar findings that currency linkages tend to rise in periods of economic or political uncertainty.

However, as Greenwood-Nimmo et al. (2024; p. 2) argue, these studies demonstrated the linkages between connectedness spikes and stressful events "chiefly based on visual inspection of point estimates, as opposed to a statistical analysis of the hypothesis that a change in the spillover index coincides with a given event". In this context, Greenwood-Nimmo et al. (2024) contribute to prior research investigating spillover transmission with devising a nonparametric bootstrap-after-bootstrap procedure as a simple and robust framework for the probabilistic analysis of changes in the spillover index. They employed primary data from the Diebold and Yilmaz (2009) study to determine which events caused outbreaks of volatility in the stock markets and quantify the duration of these impacts. Ultimately, they concluded that 15 out of 19 events increased the probability of a spike in the value of connectedness above 90% over the horizon, covering the contemporaneous impact and propagating up to 22 business days. The statistical significance of surges in connectedness among global currencies linked to specific events has not been analyzed yet. Such identification is crucial as only a correctly identified relationship leading from event to connectedness offers implications for market participants (Greenwood-Nimmo et al., 2024). Our present work contributes to the literature by providing such an analysis.

In earlier work, Baruník et al. (2017) delved deeper into the intricate dynamics of volatility transmission. Drawing inspiration from the seminal work of Diebold and Yilmaz (2009), they refined the original methodology to measure asymmetry, arguing that propagation of volatility differs in the context of either positive or negative shocks. Their investigation focused on the propagation effects across the seven most heavily traded currencies, with a keen emphasis on discerning between positive and negative sources of volatility. The study robustly validates the hypothesis that markets exhibit asymmetric reactions to volatility. However, it's important to note that their data sample only runs up to 2015, and since then, significant economic and political shocks have reshaped the forex landscape.

Furthermore, Baruník and Ellington (2024) suggest that volatility connectedness comprises linkages with either a transitory or persistent nature and identify differences in the timing of transitory and persistent connectedness among US stocks. Such identification is of particular interest, as these changes indicate alterations in systematic risk, which means that capturing these changes provides additional information for market participants. However, this information is also potentially important for currency markets' participants, given that the connectedness of the stock market is related to transmissions on currency markets (Uluceviz and Yilmaz, 2020). Further, the propagation of currency's volatility affects both real economy variables (Ajao, 2015; Killicarslan, 2018) as well as financial variables (Kočenda and Moravcová, 2019; 2024). Therefore, policymakers and investors actively watching portfolios might benefit from such a perspective. Patterns of the relationship between risk propagation occur due to investors rebalancing their portfolios denominated in foreign currencies, increasing exchange rate volatility (Camanho et al., 2022). Consequently, we contribute to the literature by distinguishing between persistent and transitory transmission in forex markets since this distinction has not been identified previously.

3. Data and methods

3.1 <u>Data</u>

We identify volatility connectedness among the eight globally most traded currencies whose exchange rates are quoted against the U.S. dollar (USD): the Australian dollar (AUD), the Canadian dollar (CAD), the euro (EUR), the British pound (GBP), the Hong Kong dollar

(HKD), the Chinese Yuan (CNY), the Swiss franc (CHF), the Japanese yen (JPY), and the New Zealand dollar (NZD); the data were obtained from the kibot.com database. The set of currencies is chosen for several reasons. They represent the majority of most traded currencies globally (BIS, 2022) and are formed on a very liquid market with large volumes of transactions (Lu and Yu, 1999; Han et al., 2018). These currencies are also exposed to hedging due to their heavy use by countries with high exports (Greenwood-Nimmo et al., 2016).¹ Exchange rates are quoted against the U.S. dollar (i.e. one unit of a currency in terms of the U.S. dollar), in line with a typical approach in the forex literature so that any potential domestic (U.S.) shocks are integrated into all exchange rates. The data span runs from September 27, 2009, to April 30, 2023, and we compute the daily variances from one-minute frequency data (daily variances available upon request). The descriptive statistics are provided in Table A1.

The period 2009-2023 covers several decisive events (shocks) impacting forex markets. After computing connectedness among the currencies (see section 4.1), we endogenously detect events with statistically significant impact (see section 4.1) and divide them into three types (see Appendix Table A2) - geopolitical, economic, and natural events - as in Kočenda and Bartušek (2024). Geopolitical events cover wars, threats, missiles, strikes, referendums, and distress situations tied to governmental steps. Economic events are linked to interest rate changes, sanctions, tariffs, the labor market, monetary policy steps taken by central banks, and debt crises. Then, natural shocks are connected to pandemics and natural disasters endogenously identified by the model.² The period starts with the EU debt crisis (2010-2012), which has several significant dates linked to it, and continues with shocks in the US associated with the fiscal cliff (2012) or the US government shutdown (2013) and the Bank of Japan intervention (2013). During these years, there have been further gross events, such as the annexation of Crimea by Russia (2014), BREXIT (2016), and ongoing negotiations related to it (2017 and further). Then, several shocks were associated with the US-Chinese trade war (2018-2020). Furthermore, there was a period related to the COVID-19 pandemic (2020-2021), Russia's invasion of Ukraine (from 2022 on), and actions associated with peaking inflation, from 2022 on.

¹ In this respect, the chosen currencies differ from emerging markets currencies in terms of their market dynamics (Albrecht and Kočenda, 2024). Hedging is also more expensive for emerging markets currencies.

² No natural disaster has been identified to be linked with a statistically significant increase in connectedness.

3.2 <u>Methods</u>

In our analysis, we employ several modern and adequate methods. In this short sub-section, we provide their overview and formally introduce them with all pertinent details in a Technical Appendix. First, we quantify connectedness based on the methodology of Diebold and Yilmaz (2012), who utilized a variance decomposition method based on vector autoregressions (VAR) to calculate the connectedness index. Second, we utilize a bootstrap-based method of Greenwood-Nimmo et al. (2024) to evaluate the statistical relationship between connectedness spikes and underlying events. Third, we identify persistent and transitory changes in connectedness with the procedure of Baruník and Ellington (2024) based on a TVP-VAR model with time-varying parameter heteroskedasticity. Fourth, we employ the approaches of Kroner and Sultan (1993) and Kroner and Ng (1998), who suggested utilizing conditional variance and covariance to compute hedge ratios and design optimal portfolio weights. Fifth, we employ an asymmetry-measurement method of Baruník et al. (2017) to differentiate between spillovers due to volatility stemming from currencies' appreciations and depreciations. As stated above, all technical details about the methods used are presented in a Technical Appendix.

4. Results

We present initial findings about volatility transmissions among currencies based on a static sample encompassing the entire period. The results reported in Table A3 reflect spillover effects based on Diebold and Yilmaz's (2009) spillover index. First, the extent of volatility transmission received by currencies varies, ranging from almost fifty percent for the Canadian dollar to over ninety percent for the Australian dollar, Hong Kong dollar, Chinese yuan, and Swiss franc, with such transmissions influenced by their respective past volatility. The Australian dollar (2.29%), Hong Kong dollar (0.73%), Chinese yuan (0.62%), and Swiss franc (6.58%) have gained volatility to a minimal degree from other currencies.

Furthermore, we ascertain that the euro, Japanese yen, and Swiss franc are recipients of volatility. At the same time, the Canadian dollar, British pound, and New Zealand dollar serve as transmitters of volatility toward these currencies. Moreover, the Australian dollar, Chinese yuan, and Hong Kong dollar are more neutral from the point of net spillovers. The volatility shared across currencies is notably lower than that received from their own past values, ranging from zero to twenty-five percent (Table A3). Although these findings offer insights into

volatility transmissions throughout the entire period, our dynamic sample enables us to present a more comprehensive and detailed depiction.

4.1 Dynamic connectedness and its association with shocks

As stated earlier, empirical studies have established a positive link between increases in connectedness and episodes of economic distress, but none have authoritatively confirmed a statistically significant association between specific events and the observed rise in connectedness on the global forex market. Additionally, existing research does not adequately examine the leading indicator between connectedness and the occurrence of specific events. For that, we employ the bootstrap-after-bootstrap procedure developed by Greenwood-Nimmo et al. (2024) to statistically confirm the link between endogenously detected shocks and sudden increases in the level of connectedness of the global currencies. We identify twenty-three endogenously chosen events that affect connectedness within one business month at 90% or higher probability. We distinguish between economic, geopolitical, and natural stressful events and the length of the lag, where we cover the immediate reaction on the event day followed by the reaction on the next day. Then, we assess the response five, ten, and twenty-two days (one business month) after the event occurred.³

The first significant event that had an impact was the US debt ceiling crisis on August 2, 2011. The event caused concerns about the US defaulting on its debts, as lawmakers disagreed on fiscal reforms. As a result of worries, the US dollar volatility spiked against all major currencies. Figure 1 indicates an increase in values of connectedness, which is further confirmed in Table 1. Our findings show that the effect of this event on the connectedness of currencies was delayed, as it affected the selected currencies five, ten, and twenty-two days later. The results were consistent for both orthogonal and generalized computations.

The second event pertains to the EU debt crisis. The ECB announced the longer-term refinancing operations (LTROs) on December 8, 2011, to bolster bank lending and reduce uncertainty. Additionally, the ECB proposed further easing monetary conditions, including reducing the reserve ratio from 2% to 1% (ECB, 2011). The market perceived the

³ We present a fairly detailed description of the events linked to the endogenously detected dates. We wish to ensure that all events are clearly identified and discussed to prevent any notion about data mining on our side.

announcement positively, significantly impacting connectedness, particularly ten and twentytwo days later.

In June 2012, Greece held a closely watched parliamentary election on June 18, primarily due to ongoing debt consolidation issues. Ultimately, the newly elected party was expected to accept the bailout, ensuring Greece remained in the euro area and signaling progress in consolidation talks. The result was interpreted as a positive shock for the euro area, and in Table 1, we confirm its impact on connectedness among other global currencies.

In November 2012, the United States encountered a series of tax hikes and spending reductions intended to mitigate the budget deficit. However, these measures raised apprehensions regarding potential economic contraction (Baker et al., 2016). Concerns intensified on November 29 when negotiations regarding alterations to the proposed measures were rejected by the Republicans, with their implementation slated for the start of 2013. Notably, this period witnessed a peak in the value of the connectedness index (Figure 1). Subsequent analysis in Table 1 confirms that this event impacted volatility transmission among global currencies, which became evident one month later.

On April 5, 2013, the Bank of Japan intervened in the forex market, impacting the connectedness among global currencies. This intervention was one of four events that influenced connectedness on the same day (Table 1). Such interventions involve central banks directly buying or selling currency in the markets. This particular intervention was part of a broader strategy to combat deflation and stimulate the Japanese economy. It led to the introduction of a massive monetary easing program known as "quantitative and qualitative monetary easing" (QQE). The QQE aimed to double the monetary base and purchase large amounts of government bonds and other assets to achieve a 2% inflation target within two years (FED, 2013).

Another shock that affected selected currencies was linked to the Greece debt crisis. Another date refers to the approval of austerity measures by the Greek parliament (July 17, 2013). Such an approval was interpreted as a positive surprise as these measures were very unpopular including wage cuts, tax reforms, and budget cuts (Council on Foreign Relations, 2018). The impact of the Greek crisis was demonstrated earlier (Albrecht and Kočenda, 2023), but we document the impact of the announcement on the volatility connectedness up to one business month ahead. Such a delay enables investors to hedge portfolio positions in advance as the events occur (Greenwood-Nimmo et al., 2024). There is a difference between orthogonalized and generalized computations, but generalized computations are more sensitive to specific dates (Diebold and Yilmaz, 2009; Greenwood-Nimmo et al., 2024). On September 27, 2013, a partial government shutdown in the United States caused significant financial market turbulence, including forex market, due to its implications on budget, spending, and debt. The event marked the resolution of a sixteen-day-long dispute in the Senate related to the healthcare system known as Obamacare. The timing of this event offers valuable insights into the lead-lag dynamics of the shock, as it subsequently influenced the connectedness of currency markets one month in advance (as shown in Table 1).

The beginning of 2014 was characterized by turbulence caused by the illegal Russian annexation of Crimea. Although this was a period of increased uncertainty for several months, our model (Figure 1) indicates that the probability of an increase in connectedness was highest on March 17, 2014, when the Crimean referendum took place. The event was found to significantly impact connectedness twenty-two days ahead (Table 1). It is a crucial finding, as it follows the results for previous events and provides information about the delay. Such a leading role of the events might be particularly useful for diversifying portfolios after the event occurs (Kočenda and Moravcová, 2024).

The following shock was associated with the signing of the Minsk Protocol on September 5, 2014. The initial Minsk agreement was viewed positively, including provisions for prisoner exchanges, humanitarian aid deliveries, and the withdrawal of heavy weapons. Despite violations from both sides that eventually led to the deal's breakdown (Reuters, 2022), the currency markets reacted significantly to the first news of the agreement (see Table 1).

Spikes in 2015 were followed by further rate hikes by the Fed, which escalated by the positive surprise of the decline of US unemployment on September 4, 2015. However, positive outcomes from the labor market increased the chance of extending the hiking cycle, which increased worries about a slowdown of the economy. These surprises had an adverse impact on global risk aversion followed by safe haven currencies gaining value. Analysis of Table 1 provides evidence that this was the only event impacting all of the selected horizons of connectedness, as indicated in Figure 1.

Another market surprise was caused by the results of the UK referendum about exiting the European Union (June 23, 2016). The referendum results came as a substantial surprise to the market, which was reflected in the substantially weaker British pound (UK Parliament, 2016) and subsequent increase in volatility transmission (Figure 1). Moreover, these spillover effects exhibited a lag as the events influenced the volatility of other currencies one, five, ten, and twenty-two days in advance (Table 1). These findings emphasize the potential for hedging portfolios denominated in alternative currencies following such events. While the impact of Brexit has been previously identified (Steinberg, 2019), our study is the first to confirm these

implications in currency markets, bolstering their robustness with respect to other events as well. The occurrence of delay in transmission is of particular interest as it accentuates the need to take policy actions to watch currency and, consequently, price stabilities. Additionally, subsequent events also had an impact. On March 31, 2017, the first guidelines for Brexit negotiations were established, affecting volatility transmissions (Figure 1 and Table 1), particularly one business month later.

Then, the volatility transmission increased after North Korea launched a missile test over Japan on August 30, 2017. It increased worries impacting forex markets and increased spillover effects one month ahead (Table 1). Market uncertainty eased until December 1, 2017, when EU-UK negotiations advanced. This progress was attributed to a meeting in Dublin between Donald Tusk and Taoiseach Leo Varadkar, which received positive remarks from the President of the European Council, Donald Tusk (Europa.eu, 2018).

In July, 2018, the forex-market turbulence was linked to the US–China trade war. Even if there are more dates associated with the distress, the model identifies July 6, which was the very first date of the US implementation of tariffs on specific Chinese products. Consequently, the ban on exports affected the currency rate as the expectations about trade balance changed (Wong and Koty, 2020). The restraints affected currency markets one day, one week, two weeks and one month ahead.

On January 2, 2019, the longest U.S. government shutdown in history began, triggered by a dispute between President Trump and Congress over funding for the U.S.-Mexico border wall. The key date we identified corresponds to a meeting between President Trump and congressional leaders at the White House, marking their first face-to-face discussion about the shutdown. This event significantly impacted the nine currencies under study, affecting them one, five, and ten days after the meeting. As shown in Figure 1, volatility transmissions surged, exceeding 50%.

We identify two additional significant events related to the U.S.-China trade war. The first occurred on July 9, 2019, when the U.S. exempted 110 Chinese products from the 25% tariff, marking the first positive development in the negotiations. This initial step was followed by the exclusion of over 400 products from tariffs in September, which helped alleviate months of concerns about the trade relationship. This positive shock shifted expectations in foreign trade (Garver, 2019). Our analysis shows that this favorable news provided an opportunity to hedge portfolios one business month ahead (see Table 1), as these events served as leading indicators of currency volatility driven by changes in portfolio allocations. Further progress in

negotiations impacted volatility transmissions among the selected currencies, particularly when new regulatory guidelines were introduced for additional products on November 27, 2019.

As depicted in Figure 1, the level of market connectedness declined to approximately 40% of shared volatility until 2020. However, with the emergence of the COVID-19 virus, a significant shift occurred, resulting in a spike in connectedness to one of the highest values recorded (80%). The pandemic constituted a global economic and political shock that market participants had not previously encountered (Centers for Disease Control and Prevention, 2023). Notably, February 23, 2020, marks the onset of the virus outbreak in Italy, which escalated concerns in the Western world regarding the future outcomes of the pandemic. Our findings provide compelling evidence that this event not only intensified volatility transmission but also exhibited a delayed impact ranging from ten to twenty-two days (Table 1). In other words, despite the critical uncertainty posed by the pandemic, market participants still had a window of ten or more days to rebalance portfolios denominated in foreign currencies. While numerous studies have examined the impact of the recent pandemic on financial markets (Baker et al., 2020; Chundakkadan et al., 2022), this study stands out as the first to demonstrate its implications for market connectedness and the lead-lag dynamics of these transmissions.

Furthermore, another event that affected the connectedness among currencies contemporaneously occurred on September 9, 2021. During this day, the EU reiterated support for the protocol on Ireland/Northern Ireland. It was after the European Commission updated the ministers on the developments, and they agreed on the need to identify long-term and practical solutions to address issues experienced by citizens in Northern Ireland (Council of the European Union, 2024). The event represented another advancement in the EU-UK withdrawal. The positive news had a transitory impact, affecting shared volatility between five and ten days (Table 1).

On January 12, 2022, another significant event emerged from the economic sphere with the U.S. Consumer Price Index (CPI) announcement. The CPI release was a major surprise, hitting a 40-year high, which had a profound impact on the markets, leading to heightened volatility transmissions among currencies over the following 10 and 22 days. This finding provides valuable insights for portfolio managers, who had up to 10 days to hedge their foreign currency-denominated portfolios to mitigate risks associated with increased currency volatility. Additional events are linked to this announcement, as the inflation spike prompted the Federal Reserve to implement its largest interest rate hike in over 20 years (BIS, 2022). This study is the first to analyze the impact of this event on the propagation of volatility in currency markets. Furthermore, we identify a lag in volatility transmission, occurring between five and 22 days after the event (see Figure 1 and Table 1). The series of inflation shocks also contributed to the energy crisis in Europe, which reached a peak on August 8, 2022, when energy prices hit all-time highs.

4.2 Pre-event analysis

In this subsection, we adapted the approach of Greenwood-Nimmo et al. (2024) to examine how market expectations influence connectedness prior to key events. After identifying specific shock dates in Section 4.1., we recalculated the bootstraps to assess the impact of pre-event expectations on significant spikes in connectedness. It is important to note that some shocks are related to announcements made before actual events. For instance, a shock labeled "Weak US jobs pushed back expectations of a US rate hike" corresponds to the release of U.S. unemployment figures, which heightened the significance of the subsequent Federal Reserve meeting. Thus, these events may reflect expectation shifts or market sentiment changes.

However, the modification of the procedure to detect pre-event changes in connectedness is used in finance for the very first time and offers valuable insights into the characteristics of pre-event changes in sentiment. We detect these changes in connectedness as a result of portfolio reallocations in Table A4. However, as can be seen, none of these events were confirmed to have affected the connectedness in advance. Such a result highlights the implications of this research and underlines its robustness. Our modification of the bootstraps also offers potential for future research studying pre-event reallocations in portfolios.

4.3 <u>Robustness of association between dynamic connectedness and shocks</u>

To ensure the robustness of our findings regarding the relationship between shocks and connectedness, we conducted a modified bootstrap-after-bootstrap procedure by averaging daily volatilities over a five-day period, as in Greenwood-Nimmo et al. (2024). The approach allows us to capture a longer-term perspective and mitigate the influence of one-day spikes. The results of our robustness analysis, presented in Table A5, closely resemble those from Table 1. We consistently observe a 90% or higher probability of increased connectedness within one month for the same twenty-three events with the exemption of four events that appear rather than a one-day spike, and we don't find them statistically significant in robustness tests. Furthermore, these findings align with the leading indicator pattern, as we obtain similar results across different time horizons.

Minor variations in the results are observed in only four cases. Specifically, two events in 2011—the U.S. debt ceiling crisis and the announcement of Long-Term Refinancing Operations (LTROs) by the ECB—show a high probability of association with spikes in connectedness, with over 85% confidence for both, despite these events occurring at the tails of the time series. The other two events took place in 2017: the drafting of guidelines for the UK-EU withdrawal and a missile test by North Korea. Although the spikes appear more as one-day effects, the probability of association remains strong, exceeding 87% (Table A5). Additionally, we consistently observe similar associations with the same delay lengths for other events in the dataset.

4.4 Transitory and permanent impacts on connectedness

We have observed that the spillover effects between currencies intensified in the context of eighteen global shocks, with a delay ranging from one to twenty-two days. However, when analyzing the transitory and permanent impacts on connectedness, we gain insights into which events may be associated with permanent changes in transmissions between selected currencies and which events had only a temporary influence.

Figure 2 presents notable observations regarding the transient changes in connectedness, showcasing more prominent fluctuations ranging from 20% to 60%. However, these changes exhibit transitory characteristics, persisting for only a few days. Moreover, the frequency of transient increases in connectedness is noteworthy, which corresponds to approximately twenty-three events where the connectedness index peaked above 40%. These findings corroborate the events identified in Figure 1. Conversely, only four events throughout the selected period significantly drive the permanent impact on connectedness. The level of permanent connectedness varied between zero and ten percent. The first event, which occurred in May 2010, is not covered in the probabilistic analysis, as the rolling window for bootstrap analysis begins in June 2010. However, the method used to distinguish between transitory and permanent shocks is able to capture even earlier periods. Figure 2 illustrates a permanent effect linked to the first bailout for Greece, which took place on May 2, 2010. During this event, the IMF and EU agreed to provide 110 billion euros to Greece to help the country avoid default (IMF, 2011).

The research findings reveal several events that have had a persistent impact on the nature of connectedness between global currencies. First, the US debt ceiling crisis on August 2, 2011, caused the permanent connectedness to peak above ten percent. The event coincided

with a spike in uncertainty regarding the US default (Baker et al., 2016). Our results document a permanent 5% shift in the connectedness between currencies, and it further complements our results by statistically identifying its effect on connectedness from five days to one month ahead (Table 1).

Another event that significantly altered the nature of connectedness (Figure 2) is the referendum on the UK leaving the European Union, which took place on June 23, 2016. As shown in Table 1, this event caused a spike in connectedness up to one business month ahead throughout the observation period. The approach strengthens these findings by confirming the event as a fundamental shift in the nature of connectedness.

Last, the COVID-19 pandemic emerged as the fourth event that significantly influenced permanent connectedness among global currencies. The unprecedented global health crisis instigated a remarkable change of over 5% in connectedness, as depicted in Figure 2. While our probabilistic analysis previously revealed a delay exceeding ten days between the upsurge in connectedness and the occurrence of the pandemic, we now furnish compelling evidence of a lasting shift. Note that prior studies (e.g., Maqui and Morris, 2020; Williamson et al., 2022) have extensively examined the pandemic's impact on long-term economic development. Nevertheless, our study is the first to identify the specific influence of the pandemic on currency connectedness, thereby shedding light on the shocks that have fundamentally altered the nature of connectedness among global currencies.

4.5 Hedge ratios and portfolio weights

As financial markets continue to integrate assets denominated in different currencies, these currencies have become crucial components of investment portfolios, as highlighted by Camanho et al. (2022). Given the significant volatility and intricacy of today's financial markets, it is imperative to calculate hedge ratios and weights in portfolios precisely since they are likely to vary substantially over time. The hedge ratio is defined as the ideal quantity of asset x contracts that an investor needs to include in a portfolio for maximum protection against unfavourable market shifts. Similarly, the necessity to adapt optimal portfolio weights over time is also recognized. Therefore, our study focuses on the variation in portfolio weights and hedge ratios of most traded currencies across different time frames. The findings from this study are relevant for international portfolio diversification and effective risk management strategies. We explore to what degree and in what ways the optimal diversification approaches have evolved

during these periods in response to shifts in volatility and the patterns of connectedness observed.⁴

Our methodology, inspired by Antonakakis et al. (2018), and Kočenda and Moravcová (2019, 2024), commences with the estimation of an asymmetric dynamic conditional correlation (ADCC). Initially focusing on identifying the most fitting univariate GARCH models for each time series, we embark on a two-phase approach. The ADCC model is applied in the subsequent phase using the standardized residuals derived from the first phase. The process is pivotal in evaluating the changing volatilities, covariances, and correlations of a variety of currencies over distinct time periods. We differ from the previous studies as we identify the subperiods by the method of Baruník and Ellington (2024). The approach enabled us to examine four shocks that affected connectedness permanently and further, we used these four shocks as subperiods with different hedging parameters.

Hedging strategies play a critical role in minimizing the potential downside of an investment portfolio. Risk mitigation often comes at the cost of reduced profit potential, as there are expenses (known as hedging costs) associated with safeguarding a portfolio (Jayasinghe and Tsui, 2008). For effective and profitable hedging, investors need to understand that hedging strategies vary based on the magnitude and direction of market spillovers (Kočenda and Moravcová, 2024). To provide a comprehensive view, Table 2 presents the averaged hedge ratios and portfolio weights for all the periods we have studied. Additionally, for thoroughness, the Appendix details hedge ratios and portfolio weights in Tables A6 to A10.

We can gain helpful insights from Table 2. First, we can see that the hedging costs of both the Swiss franc (CHF) and Japanese yen (JPY) increased mainly since the beginning of Covid-19 as they are widely considered to be safe haven currencies (Kim and Lee, 2023). During the first periods, it cost 15 cents to hedge a 1-dollar position against a basket of other currencies, but the costs rose, and after Covid-19 they reached 17 cents. A higher increase could be seen for Swiss francs as the costs increased from 23 cents to 29 (Table 2). Moreover, we can see that the hedging costs of both the Chinese renminbi (CNY) and Hong Kong dollar (HKD) decreased significantly over the time periods as the 1-dollar position of other currencies could be hedged by 81 cents position of CNY during the EU debt crisis and it continually dropped to

⁴ We could have obtained this information from the directional connectedness matrix in Table A3 as used in earlier studies (e.g., Diebold and Yilmaz, 2012). However, as pointed out by Kočenda and Moravcová (2019, 2024), the hedging ratios and portfolio weights provide more detailed information about what variable is an appropriate diversification tool. It does not provide an information about the directions of spillovers but informs about weights to hedge excessive movements in one asset through a position in another asset.

13 cents. HKD dropped even more from 2,57 dollars to hedge 1-dollar position to 38 cents after the Covid-19 pandemic (Table 2).

We can also gain more insights from portfolio weight analysis (Table 2). The average weight in the bi-variate portfolio of the Chinese renminbi decreased continually over all periods when its average weight was 93% and further dropped to 70%. The portfolio's high weight is estimated due to the overall low volatility of both HKD and CNY. Then, as a result of the abandonment of the Swiss franc exchange rate commitment in 2015, the weight of CHF in the portfolio increased from 40% to 59% after the Covid-19 pandemic. It could be attributed to the strengthened franc after the end of the exchange rate commitment (Białowolski and Węziak-Białowolska, 2017). Moreover, we can see that the weight of the British pound (GBP) decreased since the period of Brexit from 54% of the average weight against the second currency to 35% (Table 2). Overall, we can confirm the rising hedging costs of CHF and JPY as a result of heightening uncertainty.

4.6 Asymmetries in the propagation of volatility

The findings discussed in earlier sections did not consider asymmetries among currencies.⁵ Now, we distinguish whether the volatility propagation comes from negative and positive shocks. Negative and positive returns reflect depreciation and appreciation and form the basis for negative and positive semivariances. In Figure 3, we illustrate the dynamics of asymmetries in connectedness and show that the effects of intra-day currency depreciation versus appreciation against the US dollar differ significantly. In general, the impact of negative shocks (below zero line) prevails over the positive shocks (above zero line); the extent of asymmetries declines over the time, though.

The disparity between positive and negative volatility amounts to approximately 20% in economic shock scenarios. Our dynamic analysis of the dataset (shown in Figure 3) reveals that negative volatility spillovers are more frequent during periods of economic hardship. This observation aligns with the findings of Baruník et al. (2017), who noted that in times of economic instability, negative volatility tends to drive connectivity more than positive volatility. The researchers documented this trend among the seven most traded currencies up to 2015. We have expanded this dataset to include additional significant economic shocks.

⁵ We do not include the Chinese yuan (CNY) and the Hong Kong dollar (HKD) in our asymmetry analysis due to data problems as it was not able to compute semivariances from our data of these two currencies.

Moreover, when positive volatility dominates, the most traded currencies tend to appreciate relative to the US dollar, as depicted in Figure 3. These dynamics are consistent with Baruník et al. (2017) conclusions that global currencies exhibit increased vulnerability under economic strain.

The pattern of asymmetries correlates with economic or political shocks (Table 1). We can see prevailing positive connectedness asymmetries in 2010 and 2012 when the EU debt crisis peaked. Then, we can observe those effects linked to the US government shutdown (November/December 2013), followed by the BREXIT referendum (June 23, 2016), and then in late February 2022, when Russia invaded Ukraine. Moreover, we can see that the asymmetries decreased over time since they ranged between $\pm 20\%$. Then, from 2016, the maximum asymmetry in propagation in volatility was due to the Russian invasion (around 10% from currencies' depreciation).

4.7 Connectedness at tails

In our preliminary evaluation, we explore the dependency of returns linked to extreme values that can emerge amid market disruptions. Such disruptions are predominantly instigated by negative news events (refer to the 0.05 quantile in Table A11) or favorable news (refer to the 0.95 quantile in Table A12). Furthermore, we derive a measure of average connectedness (at the 0.50 quantile, see Table A3), which aligns closely with the traditional total return connectedness. Our static sample analysis utilizing quantile VAR shows that, under typical market conditions, variables are largely driven by their own past returns (evident in Table A3). Conversely, during extreme conditions caused by significant positive or negative events, cross-variable transmission effects become more significant (see Tables A11 and A12). These observations are consistent with earlier findings of Albrecht et al. (2023).

Tables A11 and A12 provide the results for a static sample, illustrating the connectedness and volatility transmissions among selected currencies over the entire period. A notable finding, in contrast to other asset classes (as noted by Albrecht et al., 2024), is that these currencies display a relatively lower share of returns originating from their own previous values. The finding suggests a high degree of interconnectedness between currencies, as they generally receive only 10-25% of returns from their own history. These transmission patterns remain consistent across all three connectedness regimes, confirming the robustness of the results. In a static sample, these net transmissions reach up to 15%, either for positive or negative returns.

We can further analyze dynamic samples (see Figure 4) for more granular insights. While Albrecht et al. (2023) explored standard connectedness, they considered only transmission among commodity currencies. However, the differences observed are relatively minor. During periods of positive market conditions, the connectedness among these commodities remained stable, with 75-100% of returns shared. Dynamic samples reinforce our earlier conclusions regarding similar transmission patterns across all three market environments. The result is significant, as the role of return transmission is not found with other asset classes (see, for example, Ando et al., 2022). Under market stress, volatility propagation becomes more dynamic ranging from 75% to 100% across these currencies, indicating heightened connectedness during times of turmoil. The findings align with previous quantile-based research (e.g., Ando et al., 2022; Albrecht et al., 2023), though they have not been previously identified for this set of currencies.

4.8 Linkages between connectedness and indicators of uncertainty and liquidity

In Table 3, we provide results of the interplay between connectedness and its potential determinants (Menkhoff et al., 2012; Davis et al., 2022; Della Corte et al., 2022; Albrecht and Kočenda, 2024): uncertainty (proxied by U.S. Economic policy uncertainty index (EPU)), liquidity (proxied by euro-dollar bid-ask spread and TED spread), economic activity (proxied by S&P500), monetary policy (proxied by U.S. 5-year yield (US5Y)), and credit risk (proxied by U.S. 5-year credit default swaps (US CDS)).⁶

Hence, we regress connectedness on five key factors: EPU, TED (USD/EUR bid-ask spread in the second specification), US5Y, and SP500 ($Conn = \alpha + \beta_1 EPU + \beta_2 TED + \beta_3 ldSP500 + \beta_4 US5Y + \beta_5 US_CDS + \varepsilon_i$). The motivation for conducting this analysis lies in the transmission of uncertainty. Investor behavior is significantly influenced by uncertainty, which becomes even more pronounced during economic and political shocks. When these shocks occur, investors adjust their portfolios due to the heightened uncertainty regarding the

⁶ The Economic Policy Uncertainty Index (EPU) is a market index that gauges the uncertainty values based on textual analysis from the newspapers (Albrecht et al., 2023). The TED spread is a crucial financial indicator that reflects the difference between the three-month Treasury bill rate and the three-month LIBOR (London Interbank Offered Rate) based in U.S. dollars. The TED spread is used to measure liquidity (FED, 2008). Moreover, liquidity risk is further associated with other types of risks, including sovereign risk (López-Espinosa et al., 2017); we also employ a separate measure for credit risk following Menkhoff et al. (2012), and we further check the influence of monetary conditions proxied by the US 5-year yield (Della Corte et al., 2022).

⁷ The correlation matrix among determinants is provided in Table A13.

future impact on their investments (Albrecht et al., 2023). This adjustment, in turn, affects currency markets (Camanho et al., 2022). Additionally, during such shocks, concerns about negative portfolio revaluations lead to a substantial reduction in market liquidity (Albrecht and Kočenda, 2024), significantly impacting forex interconnectedness. Risk aversion drives increased transmission effects (Tran, 2019) as investors seek to protect themselves against potential negative revaluation (Camanho et al., 2022). Moreover, as Menkhoff et al. (2012) demonstrate, the volatility in currency markets is affected by carry trades, which are directly affected by interest rates. Therefore, we follow their findings to evaluate the impact of monetary policy on connectedness. Della Corte et al. (2022) built on these findings to reveal volatility propagated among currency rates as a result of an increase in credit risk. These factors directly affect economic conditions within countries resulting in changes in economic activity, which further leads to increased volatility transmissions (Davis et al., 2022; Albrecht and Kočenda, 2024).

Our findings reveal a statistically significant association between volatility connectedness and these factors, albeit at different levels of economic significance. First, evidence on the link between uncertainty and connectedness values indicates that connectedness intensifies when uncertainty heightens, however, only to a small extent. A channel of this propagation is that increased uncertainty prompts investors to rebalance their portfolios in foreign currencies due to increased risk aversion (Tran, 2019). It subsequently leads to increased currency market volatility that transmits across currencies (Camanho et al., 2022). However, the economic significance of uncertainty is much lower than that of liquidity.

Second, the link between the TED rate and connectedness accentuates the impact of liquidity on the connectedness of most traded currencies. We show that higher TED spreads, indicating a worse liquidity situation in the market, correspond to greater connectedness, which aligns with the evidenced relationship between shocks and liquidity, as liquidity tends to deteriorate during market turbulence (Bratsiotis and Theodoridis, 2022). We found similar results when we replaced the TED rate with the euro-dollar bid-ask spread as a proxy for liquidity (Albrecht and Kočenda, 2024). Our analysis shows that deteriorating liquidity has a significantly greater impact on connectedness than uncertainty.

However, despite the findings of previous studies (Davis et al., 2022; Albrecht and Kočenda, 2024), we do not confirm a relationship between economic activity and connectedness for both equations (Table 3). However, following Menkhoff et al. (2012) and Della Corte et al. (2022), we reveal statistically significant relationships between connectedness and its drivers: credit risk and interest rates. The findings for credit risk indicate that an increase

in credit risk has a positive influence on connectedness causing it to rise. However, if the yield of the U.S. bonds rises, it has a diverse effect on volatility connectedness among the currencies. The findings remain robust across both specifications.

5. Conclusions

Our study offers a comprehensive analysis of volatility connectedness among most traded currencies spanning a period of fifteen years, from September 2009 to April 2023. We employ a novel method to quantify the statistical likelihood of increased volatility connectedness resulting from specific economic, geopolitical, and natural shocks affecting global currencies. The empirical results from our analysis reveal a significant rise in connectedness within a one-month timeframe after the occurrence of twenty-three endogenously chosen global events, surpassing a probability threshold of 90%. It highlights the role of shocks in amplifying connectedness among global currencies. Moreover, the probability of an immediate increase in connectedness on the same day as the event was higher than 90% in only two of the eighteen cases, indicating a delay in the DY index's response to stressful events. Such delay offers potential avenues for implementing effective hedging strategies to mitigate foreign exchange risk.

Furthermore, our study introduces the application of Baruník and Ellington's (2024) method to forex markets, providing a novel distinction between the temporary and lasting effects of specific events. Four events throughout the examined period resulted in a permanent 10% shift in the connectedness among most traded currencies; two events are associated with the EU and US debt crises. Then, we build upon these four shocks and divide the sample into five sub-periods to examine optimal weights in portfolio and hedging ratios for investors. Following the approach of Kočenda and Moravcová (2019), we compute the exact hedging ratios and portfolio weights to identify the euro and Japanese yen as the two currencies most suitable for portfolio optimization. We examine these ratios as the first study for most traded currencies. Also, we accounted for the dynamics of asymmetries in connectedness and showed that the effects of intra-day currency depreciation versus appreciation against the US dollar differ significantly. We find that these effects decreased by 10% over the period. In general, the impact of negative shocks (below zero line) prevails over the positive shocks (above zero line); the extent of asymmetries declines over time, though. Additionally, our regression analyses confirm the relationship between connectedness and proxies for uncertainty, credit risk, monetary policy, and liquidity.

Our study reveals a pertinent policy implication concerning the dynamics of volatility connectedness in response to economic, geopolitical, and natural shocks. Specifically, we find a notable increase in connectedness for approximately one business month following statistically significant shocks. The finding holds weighty practical implications for forex portfolio management, as it provides investors with a valuable timeframe of twenty-two business days to effectively hedge portfolios denominated in foreign currencies after an economic or political shock occurs. Furthermore, central banks can benefit from these results, too, in the context of their role to enhance price stability linked to currency stability.

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Technical appendix

A1: Connectedness measure

Diebold and Yilmaz (2009, 2012) quantified interconnectedness among assets based on variance decompositions from vector autoregression (VAR) models. This model measures how shocks originating in one asset influence the price volatility of others, representing a "spillover" effect crucial to understanding systemic risk. Diebold and Yilmaz spillover index, or a connectedness measure, has become a standard tool used in the literature.⁸ In the below description, we closely follow the seminal exposition.

We calculate the daily variances from the intraday one-minute close prices for each currency and form realized volatilities $RV_t = \sum_{i=1}^p \Phi_i RV_{t-i} + u_t$. Here, u_t is an array of independent and identically distributed (*iid*) errors, and Φ_i represents p coefficient matrices. We obtain the moving average for the invertible VAR process ($RV_t = \sum_{i=0}^p A_h u_{t-i}$) using the recursive formula $A_i = \sum_{j=1}^p \Phi_i A_{i-j} + u_t$, where $A_0 = I_n$ for i < 0.

The technique involves linking the variance decomposition matrix to the vector autoregression model with *N*-variables. The method of Diebold and Yilmaz (2012) allows us to determine the proportion of variance in the *H*-step forecast errors x_i , the proportion of variance against shocks x_i , and the proportion of variances among variables, referred to as connectedness. Connectedness is defined as the portion of the *H*-stepped forecast errors contained in the forecast x_i against shocks in the x_j variable (i,j=1,2,...,N, while). The contribution of the *j* component to the forecast error in the *i* component is defined as follows:

$$\theta_{ij}^{g}(H) = \frac{\sigma_{jj}^{-1} \sum_{h=0}^{H-1} (e_i' A_h \sum e_j)^2}{\sum_{h=0}^{H-1} (e_i' A_h \sum A_h' e_i)}$$
(1)

At time *t*, A_h represents the moving average forecast coefficient. Note that the sum of decomposed variances in each row may not sum to 1, as $\sum_{j=1}^{N} \theta_{ij}^{g}(H) \neq 1$. σ_{jj} denotes the standard deviation of the error component, while e_j and e_i are selection vectors (Bubák et al., 2011). The authors define the total connectedness index as the contribution of shocks to the total forecast error variance of the variable set:

$$S^{H} = \frac{\sum_{j=1}^{N} S_{i \leftarrow j}^{H}}{\sum_{i,j=1}^{N} S_{i \leftarrow j}^{H}} = \frac{\sum_{i,j=1}^{N} S_{i \leftarrow j}^{H}}{N}$$
(2)

⁸ The code to perform procedure of Diebold and Yilmaz (2009, 2012) is available at <u>https://www.mathworks.com/matlabcentral/fileexchange/74563-diebold-and-yilmaz-2009-2012-2014-spillover-index</u>

The sum of *H*-step spillovers for each matrix row is equal to $1 (\sum_{j=1}^{N} S_{i \leftarrow j}^{H} = 1)$, whereas the total spillovers for all variables are $N (\sum_{i,j=1}^{N} S_{i \leftarrow j}^{H} = N)$. Normalization of volatility spillover and the contribution from variable shocks is carried out using the total forecast error variance decompositions. A rolling window of 200 days from t-199 to t is used to capture the dynamics of connectedness.⁹ Consistent with Bubák et al. (2011), a VAR lag length of 2 and a forecast horizon of H=10 are selected.¹⁰ Finally, the employed approach is compatible with the testing methodology described in section 3.3.

A2: Statistically significant links between connectedness and impactful events

The total connectedness index of Diebold and Yilmaz, introduced in section A1, can provide information about the impact of shocks and resulting spikes in connectedness. However, it does not reveal any information about the statistical significance of individual spikes in relation to specific events. We utilize a bootstrap-based method developed by Greenwood-Nimmo et al. (2024) that enables us to identify statistically significant links between connectedness spikes and underlying events. Despite its recent novelty, the method of Greenwood-Nimmo et al. (2024) has already been used in several financial analyses (e.g., Albrecht et al., 2023; Kočenda and Bartušek, 2024; Albrecht and Kočenda, 2024).

In the following description, we closely follow exposition of Greenwood-Nimmo et al. (2024).¹¹ The method begins with computing the Diebold and Yilmaz connectedness measure as in specification (2) and involves two stages of bootstrapping. The first stage generates bias-corrected bootstrap estimates. We summarize the steps of the method used on an orthogonalized connectedness index (which depends on variable ordering) as follows: (i) estimate and save the residuals \hat{u}_t , the (orthogonalized) connectedness index values S^{Ho} , and the parameter estimates \hat{A}_i ; (ii) retrieve *B* bootstrap samples from x_t .

$$x_t^{(b)} = \sum_{j=1}^p \hat{A}_j x_{t-j}^{(b)} + u_t^{(b)}$$
(3)

⁹ The rationale for this selection is the potential presence of discontinuities arising from unstable rolling samples when a substantially shorter window length is employed (Diebold and Yilmaz, 2012). We conducted a sensitivity analysis utilizing a window length of 200 days, and significant events were detected in the connectedness metrics under both rolling windows (100 and 200 days).

¹⁰ We compute the total connectedness index and do not assess directional spillovers because the issue has been covered in several earlier analyses. When employing the VAR model, we follow the standard in the literature to make our results directly comparable with other published findings (e.g., Diebold and Yilmaz, 2014; Uluceviz and Yilmaz, 2020).

¹¹ The code to perform procedure of Greenwood-Nimmo et al. (2024) is available at <u>https://data.mendeley.com/datasets/rtwsfgpgmf/1</u>

The VAR residuals are used to calculate $u_t^{(b)}$, with *p* given as the initial value. (iii) Next, *B* bootstrap samples are generated and used to re-estimate the VAR model. This results in new estimates for the residuals, connectedness index, and parameters. (iv) The formula used to estimate the bias between the bootstrap measurements is $\hat{Y}_o = B^{-1} \sum_{b=1}^{B} S_{Ho}^{(b)} - S_{Ho}$. (v) The entire process of steps (ii) to (iv) is then repeated to obtain new *B* estimates through bootstrapping, with the bias \hat{Y}_o subtracted each time. Finally, (vi), all steps (i)-(v) are repeated for each observation in the rolling sample to provide statistical information for all observations.

We use the aforementioned procedure to compute the probability of a statistically significant association between a specific event (day) and a particular value (spike) of the connectedness measure. To observe the reaction before and after the shock during the specific period, we calculate the generalized connectedness index.¹² The index provides an average value over the selected period. We perform the probability analysis using the same settings as Greenwood-Nimmo et al. (2024), including a 2-step lag value, a 10-step ahead forecast, and a 200-step window.¹³

The method detects statistically significant increases or spikes in connectedness. Following Greenwood-Nimmo et al. (2024; section 2.4), we assess whether there are discernible changes in connectedness intensity across subsequent rolling samples compared to one or more previous rolling samples. Particularly, we continuously compute the probabilities specified in equation (4) as the rolling samples develop:

$$Prob\left(100 \times \left[\frac{S_{t+i} - \bar{S}_{t-j}}{\bar{S}_{t-j}}\right] > \alpha\right), i \in \{0, 1, ...\}, j \in \{1, 2, ...\},$$
(4)

In our analysis, we calculate the spillover index denoted as S_{t+i} by employing bootstrapping techniques on a rolling sample that concludes on day t+i. As a reference point, \bar{S}_{t-j} represents the average spillover index across numerous bootstrap samples within the determined rolling window.

¹² In our robustness analysis, we focus on two distinct pre-event comparison periods. The first period corresponds to the trading day immediately preceding a specific event. However, we recognize that conditions on the day prior to an event may not always be fully representative due to outliers in the data or potential information leakage. For that, we adopt an alternative approach. Specifically, we compute the average spillover over the entire week preceding the event as our basis for comparison. This 5-day average, as proposed by Greenwood-Nimmo et al. (2024), provides a more stable measure of pre-event conditions.

¹³ We have conducted robustness checks concerning forecast horizons set at 8, 10, and 12, along with VAR lag lengths spanning from 1 to 3. Outcomes derived from varying horizons and lag lengths exhibit no substantial deviations from our benchmark results and have no impact on our conclusions. As the details would substantially extend the paper, we opt for the above brief summary.

To detect significant events with substantial changes in the spillover index, we propose the following approach: First, set j = l and consider, $i \in \{0,1,5,10,22\}$. Next, define α as 5%, representing the degree of variation in the connectedness index. Now, whenever the likelihood at time t+i (where i = 0) exceeds or equals 90%, we identify day t as a statistically significant event. Such events lead to a change of 5% or more in the connectedness index. By specifying $i \in \{0,1,5,10,22\}$, we can draw statistical inferences about the impact of shocks on connectedness occurring 1, 5, 10, and 22 days after the event.

Given its novelty, the proposed methodology lacks a viable alternative. Specifically tailored for the Diebold and Yilmaz (2009, 2012) connectedness index (DYCI), this method adheres to a frequentist framework. Consequently, its seamless adaptation to the TVP-VAR approach, a Bayesian counterpart, remains elusive. Notably, its strengths lie in its distinctive nature and precise identification of shocks, a hallmark of the widely adopted Diebold and Yilmaz (2009, 2012) procedure that dominates the field.¹⁴

A3: Transitory and permanent impacts on connectedness

We identify persistent and transitory changes in connectedness that are due to specific impactful events with the procedure of Baruník and Ellington (2024).¹⁵ In their procedure, they propose that the economy follows a TVP-VAR model with time-varying parameter heteroskedasticity, as $X_{t,T} = \Phi_1(t/T)X_{t-1,T} + \cdots + \Phi_p\left(\frac{t}{T}\right)X_{t-p,T} + \varepsilon_{t,T}$. We estimate the TVP-VAR with the quasi-Bayesian local likelihood (QBLL) estimation technique of Petrova (2019) to obtain the time-varying coefficients and covariance matrices at a specific time point $u = t_0/T$, such as $\hat{\Phi}_1(u), \ldots, \hat{\Phi}_p(u)$ and $\hat{\Sigma}(u)$. The proposed method involves a kernel weighting function assigning greater importance to observations close to the period of interest for the coefficients and covariance matrices. Following Baruník and Ellington (2024), we use a Normal kernel with the weight W=8. We use the Bayesian estimation approach, which makes it possible to construct network measures with confidence intervals based on the parameter distribution. Because of the use of conjugate priors, the posterior distribution of the model parameters is analytical. It

¹⁴ In their seminal work, Greenwood-Nimmo et al. (2024; section 2.3) conducted a simulation study. The findings demonstrate that irrespective of whether the shift in the Diebold-Yilmaz Spillover Index reflects a transient or permanent change, their proposed method effectively detects alterations in the interrelationships among the model's data series. Consequently, the simulation exercise provides robust evidence supporting the method's capacity to identify statistically significant shifts in connectedness.

¹⁵ The code to perform procedure of Baruník and Ellington (2024) is available at <u>https://github.com/barunik/DynamicNets</u>

eliminates the need for Markov chain Monte Carlo simulation algorithms and enables parallel computing (Baruník and Ellington, 2024).

We use finite horizon *H* to estimate the dynamic adjacency matrix ($\hat{\theta}$) with the aim of limiting the infinite VMA(∞) representation of the approximating model. Horizon *H* approximates the frequency domain and holds no importance in the time domain. Following the previous approach of Baruník and Ellington (2024), we use a truncation horizon of 100 in our study. The method we use to estimate the *j*, *k* element of the dynamic adjacency matrix involves determining between the transitory and persistent components of the matrix. We do it by examining the horizon d = (a, b), where *a* and *b* are both within the range of $(-\pi, \pi)$, with *a* < *b*, and at time $u = t_0/T$. The dynamic adjacent matrix is then defined as:

$$\left[\hat{\theta}(u,d)\right]_{j,k} = \frac{\hat{\sigma}_{kk}^{-1} \sum_{\omega \in d} \left(\left[\hat{\Psi}(u,\omega)\hat{\Sigma}(u)\right]_{j,k}\right)^2}{\sum_{\omega \in (-\pi,\pi)} \left[\hat{\Psi}(u,\omega)\hat{\Sigma}(u)\hat{\Psi}^T(u,\omega)\right]_{j,k}}$$
(5)

The estimate for the impulse transfer function $\widehat{\Psi}(u, \omega)$ is obtained by taking the inverse Fourier transform of a finite set of impulse response functions covering a specific horizon. Specifically, we compute $\widehat{\Psi}(u, \omega)$ as the weighted sum of $\widehat{\Psi}(u, h)$ for $h \in \{0, 1, ..., H-1\}$, where *H* is the chosen truncation horizon as in Baruník and Ellington (2024). The resulting frequency range $\omega \in \{aH/2\pi, ..., bH/2\pi\}$ can be interpreted according to the time scale of interest. For daily data, we interpret the transitory (short-term) network as the frequency range corresponding to horizons of 1 to 5 days and the persistent (long-term) network as the frequency range corresponding to horizons greater than 20 days. It requires setting the band as $(a, b) = (2\pi/5, 2\pi)$ for the transitory network and $(a, b) = (0, 2\pi/5)$ for the persistent network. By estimating Equation (2) and its modifications to directional spillovers, we directly obtain estimates of the dynamic adjacency matrix defined in (4) for the specified time scales as in Baruník and Ellington (2024).

A4: Portfolio weights and hedge ratios

In his theory of optimal portfolio, Markowitz (1991) presents a concept where the optimal portfolio achieves the highest expected return for a given level of market risk. Kroner and Sultan (1993) and Kroner and Ng (1998) developed a procedure to quantify hedge ratios and portfolio weights to build optimal portfolios.¹⁶ The method is based on deriving conditional variances

¹⁶ The code to run the procedure of Kroner and Sultan (1993) and Kroner and Ng (1998) is available at https://cran.r-project.org/web/packages/rmgarch/rmgarch.pdf

and covariances from an asymmetric dynamic conditional correlation GARCH model (ADCC-GARCH). The procedure has become a standard tool in the financial literature and in the following description we follow the seminal exposition.

Initially, we determine the suitable GARCH models for every currency over a distinct time frame. Following this, the optimal diversification for the global currencies is computed using time-varying conditional correlations derived from the second stage of the ADCC model estimation. The methodologies of Kroner and Sultan (1993) and Kroner and Ng (1998) are influential in this context; they utilize conditional variance and covariance to compute hedge ratios and design optimal portfolio weights. The hedge ratio is computed as $\beta_{j,k,t} = h_{j,k,t}/h_{k,k,t}$ where $h_{j,k,t}$ represents the conditional covariance between the global exchange rates *j* and *k*, while $h_{k,k,t}$ denotes the conditional variance of currency *k* at time *t*. The implication of this formula is that a long position in a currency (for instance, *j*) can be offset by taking a short position in a different currency (such as *k*). For a portfolio comprising two currencies, the optimal weights for currency *j* and *k* at a specific time, *t*, are determined using the formula below:

$$w_{j,k,t} = \frac{h_{kk,t} - h_{j,k,t}}{h_{jj,t} - 2h_{jk,t} + h_{kk,t}} \,. \tag{6}$$

In equation (6), $w_{jk,t}$ denotes the weight assigned to currency *j*, while $(1 - w_{jk,t})$ represents the weight of currency *k*. The composition of the portfolio, as indicated by these weights, adheres to the conditions outlined below:

$$w_{j,k,t} = \begin{cases} 0, & if \ w_{jk,t} < 0\\ w_{jk,t} & if \ 0 \le w_{jk,t} \le 1.\\ 1, & if \ w_{jk,t} > 1 \end{cases}$$
(7)

The same methodology has recently found application in empirical finance research, notably in the study of Central European currencies conducted by Kočenda and Moravcová (2019) and in the exploration of energy commodities by Kočenda and Moravcová (2024).

A5: Measuring asymmetries

To quantify and assess asymmetries in forex connectedness, we employ the method of Baruník et al. (2017), which is a modification of the technique shown in Baruník et al. (2016); the

modification is relevant to analyzing the forex market. The method has become an established tool in the literature and in the following account, we closely follow the seminal exposition.¹⁷ The forex connectedness is calculated in the same manner as in specification (1). However, instead of realized variance, realized semivariances are used. The semivariances are effectively constructed from positive and negative returns that directly correspond to appreciation and depreciation, respectively. Formally, forecast error variance decomposition matrix in a VAR model is computed with negative and positive daily semivariances ($RS_t^+ = \sum_{i=1}^p \phi_i RS_{t-i}^+ + u_t$; $RS_t^- = \sum_{i=1}^p \phi_i RS_{t-i}^- + u_t$).

Baruník et al. (2017) defined the asymmetry of the currencies as the difference between spillovers stemming from positive and negative semivariances and termed it the Spillover Asymmetry Measure (SAM). Using the asymmetry-measurement approach, the formula for directional spillover from one currency to a group of others is specified as follows (Baruník et al., 2017):

$$S_{2Ni \to j}^{H} = 100 \times \frac{1}{2N} \sum_{\substack{i=1, i \neq j \\ |i-j| \neq N/2}}^{2N} \theta_{ij}^{g}(H) \quad i, j = 1, ..., 2N$$
(8)

From this equation, we define the equation for the net asymmetric directional index as the difference between the net spillover transmission from positive/negative volatility. We subtract the impact of "the (N+i)-th column of the spillover matrix from the effect of the *i*-th column" (Baruník et al., 2017, p 44):

$$SAM_{2N,i \to j}^{H} = S_{2N,i \to j}^{H} - S_{2N,(i+N) \to j}^{H} \qquad i, ..., N.$$
(9)

The index SAM_{2N}^{H} quantifies differences between the connectedness resulting from positive and negative shocks across all chosen currencies, defined as $SAM_{2N}^{H} = \sum_{i=1}^{N} S_{2N,i \rightarrow j}^{H} - \sum_{i=N+1}^{2N} S_{2N,i \rightarrow j}^{H}$. Comparable to how directional asymmetry is assessed in Equation 9, SAM_{2N}^{H} provides insights into the asymmetry of shocks from positive/negative volatility. Should the measure's value be positive (negative), it indicates that the spillover impact from positive (negative) volatility on all assets exceeded that from negative (positive) volatility. As in section 3.1., we employ a 200-day rolling window spanning from day *t-199* to day *t*, we set the forecast horizon H=10 and the VAR lag length at 2 as in Baruník et al. (2017) to ensure consistency of our results in terms of comparison.

¹⁷ The code to run the procedure of Baruník et al. (2017) is available at <u>https://github.com/barunik/sam2N</u>

Figure 1: Total connectedness index



Note: the y-axis could be interpreted as the percentage of shared volatility between the sample set of currencies. The results of this figure are for the currency pairs USD/AUD, USD/CAD, USD/CHF, USD/CNY, USD/GBP, USD/HKD, USD/JPY, USD/NZD and USD/EUR. The dataset encompasses the period from September 27, 2009, to April 30, 2023, and we calculate the daily variances using data at one-minute intervals. The Total Connectedness Index is calculated based on specification (2): $S^{H} = \frac{\sum_{i,j=1}^{N} S_{i,j=j}^{H}}{\sum_{i,j=1}^{N} S_{i,j=j}^{H}} = \frac{\sum_{i,j=1}^{N} S_{i,j=j}^{H}}{N}$.





Note: The full line represents a change in the connectedness longer than 30 days, while the dotted line represents the impact of up to five days, as interpreted in Baruník and Ellington (2024). Shock affecting connectedness for more than one-month changes dynamics in assets persistently as argued by Corsi and Renò (2012). The dataset encompasses the period from September 27, 2009, to April 30, 2023, and we calculate the daily variances using data at one-minute intervals. TVP Network Connectedness index is calculated $\frac{\partial \bar{u}_{1}}{\partial x} \sum_{w \in d} \left[\left[\Psi(u, \omega) \hat{\Sigma}(u) \right]_{1} \right]^{2}$

based on specification (5): $\left[\hat{\theta}(u,d)\right]_{j,k} = \frac{\hat{\sigma}_{kk}^{-1} \sum_{\omega \in d} \left[\left[\hat{\Psi}(u,\omega)\hat{\Sigma}(u)\right]_{j,k}\right]^2}{\sum_{\omega \in (-\pi,\pi)} \left[\hat{\Psi}(u,\omega)\hat{\Sigma}(u)\hat{\Psi}^T(u,\omega)\right]_{j,k}}$

Figure 3: Spillover asymmetry measure



Note: The spillover asymmetry index evaluates the overall spillover from positive volatility against the total spillover from negative volatility among four currencies. These findings pertain to the currency pairs USD/AUD, USD/CAD, USD/EUR, USD/GBP, USD/JPY, USD/CHF, and USD/NZD. The dataset encompasses the period from September 27, 2009, to April 30, 2023, and we calculate the daily variances using data at one-minute intervals. Spillover Asymmetry Measure is calculated based on specification (9): $SAM_{2N,i\rightarrow j}^{H} = S_{2N,i\rightarrow j}^{H} - S_{2N,(i+N)\rightarrow j}^{H}$ *i*, ..., *N*.



Figure 4: Total connectedness index at the lower and upper quantiles

Note: the y-axis could be interpreted as the percentage of shared volatility between the sample set of currencies at the lower (0.05) and upper (0.95) quantiles. The results of this figure are for the currency pairs USD/AUD, USD/CAD, USD/CHF, USD/CNY, USD/GBP, USD/HKD, USD/JPY, USD/NZD and USD/EUR. The dataset encompasses the period from September 27, 2009, to April 30, 2023, and we calculate the daily variances using data at one-minute intervals. The Dynamic Quantile Connectedness index is calculated based on specification (2): $S_{0,95}^{H} = \frac{\sum_{i,j=1}^{N} Q_{0,95}(S_{i-j}^{H})}{\sum_{i,j=1}^{N} Q_{0,95}(S_{i-j}^{H})} = \frac{\sum_{i,j=1}^{N} Q_{0,95}(S_{i-j}^{H})}{N}$ and $S_{0,05}^{H} = \frac{\sum_{i,j=1}^{N} Q_{0,05}(S_{i-j}^{H})}{N} = \frac{\sum_{i,j=1}^{N} Q_{0,05}(S_{i-j}^{H})}{N}$.

Event	vent Description of the shock	1	:e+0	re	<u>+1</u>	re	+5	r _e +	·10	r _e +2	22
		OVD	GVD	OVD	GVD	OVD	GVD	OVD	GVD	OVD	GVD
1	The US debt ceiling increased	45,20	43,60	49,40	49,70	90,90	81,50	44,50	68,00	23,30	50,20
2	ECB LTRO announcement	46,70	46.00	46.80	45,80	47.80	45,40	96,60	74,40	91,50	65.40
3	Greece election	51.80	49,50	45.30	48.20	41.20	78,80	75.00	86,80	63,50	96.40
4	The US approaches a "fiscal cliff"	49.40	51.70	47.10	50.20	52.30	46.50	62.90	56.70	100.00	55.70
5	Bank of Japan intervenes	100.00	100.00	58.40	91.90	0.00	16.80	0.00	17.10	0.00	12.30
6	Greek Parliament Approves Austerity Measures	38,90	62,20	41,10	69,40	32,80	62,10	30,50	64,90	42,90	93,40
7	Debate before US government shutdown intensified	96,10	99,70	96,70	99,30	20,90	99,50	27,40	99,50	24,80	99,60
8	Crimea referendum	46,00	48,50	52,70	47,40	61,70	44,50	75,20	44,10	98,90	97,60
9	Minsk protocol	40,60	41,90	42,70	44,50	40,70	47,40	40,90	47,60	7,70	92,70
10	Weak US jobs pushed back expectations of a US rate hike	51,40	50,30	53,80	52,30	49,00	49,90	58,80	57,10	99,40	100,00
11	BREXIT referendum	92,70	93,50	99,10	98,90	98,90	98,00	96,70	97,20	96,80	97,40
12	Draft guidelines for negotiations about BREXIT	62,00	60,80	70,70	69,10	80,80	75,90	85,60	98,80	97,60	97,30
13	North Korea fires missile over Japan	45,00	44,40	44,40	44,70	60,30	19,50	57,40	43,10	95,10	84,00
14	Advancement in Brexit negotiations	65,80	68,20	64,70	64,30	67,40	67,00	69,50	65,00	99,60	97,20
15	US implements first China-specific tariffs	84,90	97,80	88,20	98,40	91,30	97,20	89,80	98,30	90,10	97,80
16	US government partial shutdown	51,40	51,00	100,00	100,00	100,00	93,00	100,00	91,30	100,00	88,10
17	US exempts 110 Chinese products from 25 percent tariffs	52,20	59,30	51,20	54,70	62,50	68,20	61,80	71,90	82,80	92,90
18	New regulatory guidelines regarding trade war with China	49,90	53,00	46.30	51.10	55.30	58,00	63,70	79,20	79,40	90.00
19	Covid outbreak in Europe (Italy)	47.60	49.00	46.60	48.20	92.90	94.50	99.30	98,90	100.00	100.00
20	Protocol on Ireland/Northern Ireland	46.60	43.60	47 50	44.00	91.50	72,70	86 40	96.60	76.20	89.60
21	40-year record inflation release	49.00	44.70	50.00	44,60	57.30	48.10	99 . 80	99 . 80	99 . 80	100.00
22	FED raises raised interest rates by largest		70.10		70.00	0	06.70		0		
23	hike over 20 years Energy and inflation crisis in Europe	74,20 54,00	70,10 56,00	75,70 99,90	78,90 98,50	97 ,50 87,40	96,50 75,20	97 ,80 23,80	96,70 41,40	98,20 20,30	96,00 44,00

 Table 1: Empirical Probability of an Increase in Connectedness after Selected Events, in Percent

Note: the table presents the empirical likelihood of the connectedness index surpassing the mean of the connectedness index over the specified r_e+j days. We employed a rolling sample approach using bootstrap samples to obtain these results. Under the "OVD" and "GVD" headings, the indicated probabilities correspond to the connectedness indices calculated using orthogonalized and generalized forecast error variance decompositions. To generate these probabilities, we followed the methodology employed by Greenwood-Nimmo et al. (2024) and conducted 1000 non-parametric replications using the bootstrap-after-bootstrap technique. The reported results pertain to the following currency pairs: USD/AUD, USD/CAD, USD/EUR, USD/GBP, USD/CHF, USD/JPY, USD/NZD, USD/CNY, and USD/HKD. The dataset encompasses the period from September 27, 2009, to April 30, 2023, and we calculate the daily variances using data at one-minute intervals. The probabilities of association between a shock and an increase in connectedness are calculated based on specification (4): $Prob\left(100 \times \left[\frac{S_{t+i}-\bar{S}_{t-j}}{\bar{S}_{t-j}}\right] > \alpha\right), i \in \{0,1, ...\}, j \in \{1,2, ...\}.$

	EU	debt crisis	Gre	ece bailout	US D	ebt Ceiling		Brexit	C	ovid-19
Currency	hedge ratio	portfolio weight								
AUD	0,19	0,24	0,19	0,26	0,14	0,29	0,15	0,40	0,19	0,22
CAD	0,21	0,45	0,21	0,41	0,21	0,52	0,17	0,49	0,26	0,61
CHF	0,23	0,44	0,12	0,40	0,17	0,36	0,19	0,52	0,29	0,59
EUR	0,27	0,56	0,19	0,40	0,19	0,39	0,19	0,49	0,28	0,52
GBP	0,21	0,47	0,21	0,55	0,23	0,54	0,08	0,32	0,20	0,35
JPY	0,15	0,29	0,12	0,36	0,13	0,36	0,14	0,32	0,17	0,26
NZD	0,16	0,18	0,18	0,30	0,07	0,27	0,13	0,37	0,19	0,26
CNY	0,81	0,93	0,21	0,88	0,14	0,79	0,05	0,62	0,13	0,70
HKD	2,57	0,94	0,46	0,95	0,54	0,99	0,36	0,95	0,38	0,98

Table 2: Averaged hedge ratios and portfolio weights for global currencies

Note: the table presents average hedge ratios and portfolio weights against all other currencies for each sub-period. The numbers summarize the findings from tables A6-A10. The dataset encompasses the period from September 27, 2009, to April 30, 2023, and we calculate the daily variances using data at one-minute intervals. The subperiods are chosen based on the events identified as the permanently affecting connectedness in Figure 2. The date for the Greece bailout is May 2, 2010, which we endogenously identify as an end to the EU debt crisis; the US debt ceiling occurred on August 2, 2011; the Brexit referendum took place on June 23, 2016, and the date for Covid-19 outbreak was endogenously selected February 23, 2020. The portfolio weights and hedging ratios are calculated based on specification (6): $w_{j,k,t} = \frac{h_{k,k,t} - h_{j,k,t}}{h_{j,t,-} - 2h_{j,k,t} + h_{k,k,t}}$.

Table 3: Drivers of Connectedness

	(1)	(2)
	US_TED as a proxy for a liquidity	Bid-ask spread as a proxy for
		a liquidity
Constant	53.77***	53.88***
	(0.72)	(0.74)
US EPU	0.01***	0.02***
	(0.00)	(0.00)
US_TED	9.29***	-
	(1.23)	-
ld_SP500	-7.92	-7.25
	(12.39)	(12.54)
US_CDS	0.07***	0.12***
	(0.02)	(0.02)
US5Y	-6.71***	-6.15***
	(0.27)	(0.26)
USD/EUR bid-ask spread	-	16.31***
	-	(5.00)
Observations	2225	2225
R² adj.	0.37	0.36

Note: *** denotes p-value < 0.01, ** p-value < 0.05, and * p-value < 0.10. US Economic policy uncertainty (US EPU) represents a proxy for uncertainty, while TED spread in the specification (1) and USD/EUR bid-ask spread in the specification (2) represent proxies for liquidity. SP500 index represents proxy for economic activity. The dataset encompasses the period from September 27, 2009, to April 30, 2023, and we calculate the daily variances using data at one-minute intervals. The regressions are calculated based on the following specification: $Conn = \alpha + \beta_1 EPU + \beta_2 TED + \beta_3 ldSP500 + \beta_4 US5Y + \beta_5 US_CDS + \varepsilon_i$.

Appendix

Table A1: Descriptive Statistics

Variables	Obs.	Mean	St. Dev.	Min	Mdn	Max	Skewness	Kurtosis	ADF Test
USD/AUD	3521	0,00	0,00	0,00	0,00	0,03	55,09	3172,90	-58,54***
USD/CAD	3521	0,00	0,00	0,00	0,00	0,00	22,61	770,17	-7,58***
USD/EUR	3521	0,00	0,00	0,00	0,00	0,00	22,42	876,07	-6,11***
USD/GBP	3521	0,00	0,00	0,00	0,00	0,00	14,93	374,31	-11,40***
USD/CHF	3521	0,00	0,00	0,00	0,00	0,01	43,27	2014,50	-24,21***
USD/JPY	3521	0,00	0,00	0,00	0,00	0,00	37,32	1809,50	-15,12***
USD/NZD	3521	0,00	0,00	0,00	0,00	0,00	9,12	154,03	-5,02***
USD/CNY	3521	0,00	0,01	0,00	0,00	0,06	52,20	2941,10	-58,04***
USD/HKD	3521	0,00	0,00	0,00	0,00	0,01	3,65	26,26	-6,17***

Source: own estimation. The dataset encompasses the period from September 27, 2009, to April 30, 2023, and provides descriptive statistics for calculated daily variances computed from the data at one-minute intervals.

Table A2: Dates of specific events

Eve	ent Description of the shock	Category	Date	Source
1	The US debt ceiling increased	Economic	02.08.2011	http://edition.cnn.com/2011/POLITICS/07/25/debt.talks.timeline/index.html
2	ECB LTRO announcement	Economic	08.12.2011	https://www.ecb.europa.eu/press/pr/date/2011/html/pr111208_1.en.html
3	Greece election	Geopolitical	18.06.2012	Greece election vote leaves Euro in balance (telegraph.co.uk)
4	The US approaches a "fiscal cliff"	Economic	29.11.2012	https://www.reuters.com/article/uk-usa-fiscal-cliff-history-
5	Pank of Japan intervenes	Feenomia	05 04 2013	idUKBRE8B21GH20121203
5	Grack Darliement Approves Austerity Measures	Georgalitical	17.07.2012	Zorscheimaneport.pur (newyorkieu.org)
0	Distance High High Strength Automatic Strength S	Geopolitical	17.07.2013	Timeline: Greece's Debt Crisis (cir.org)
7	Debate before US government shutdown intensified	Geopolitical	27.09.2013	<u>Actions - H.J.Res.59 - 113th Congress (2013-2014): Continuing Appropriations</u> Resolution 2014 Congress goy Library of Congress
8	Crimea referendum	Geopolitical	17.03.2014	Crimea referendum: Voters 'back Russia union' - BBC News
9	Minsk protocol	Geopolitical	05.09.2014	What are the Minsk agreements on the Ukraine conflict? Reuters
10	Weak US jobs pushed back expectations of a US rate hike	Economic	04.09.2015	https://www.theaustralian.com.au/news/us-jobless-rate-falls-to-51-in-august/news-
				story/ac4ee2332fc3db422f7fb95ad006e403?sv=99c5682e7d9ec9201a63f770818ac94
11	BREXIT referendum	Geopolitical	23.06.2016	<u>3</u> https://www.parliament.uk/business/publications/research/eu-
••		Scoponneur	25.00.2010	referendum/background-uk-eu-referendum-2016/
12	Draft guidelines for negotiations about BREXIT	Geopolitical	31.03.2017	<u> Timeline - The EU-UK withdrawal agreement - Consilium (europa.eu)</u>
13	North Korea fires missile over Japan	Geopolitical	30.08.2017	'All options are on the table': Donald Trump says world has received North Korea's
				message 'loud and clear' after Kim Jong-un fires missile over Japan (telegraph.co.uk)
14	Advancement in Brexit negotiations	Geopolitical	01.12.2017	<u> Timeline - The EU-UK withdrawal agreement - Consilium (europa.eu)</u>
15	US implements first China-specific tariffs	Economic	06.07.2018	<u> The US-China Trade War: A Timeline - China Briefing News (china-briefing.com)</u>
16	US government partial shutdown	Geopolitical	02.01.2019	Government Shutdown 2018, 2019: Timeline, Deadline, Reasons Explained - Business
17	US exempts 110 Chinese products from 25 percent tariffs	Economic	09.07.2019	<u>Insider</u> The US-China Trade War: A Timeline - China Briefing News (china-briefing.com)
18	New regulatory guidelines regarding trade war with China	Economic	27.11.2019	The US-China Trade War: A Timeline - China Briefing News (china-briefing.com)
19	Covid outbreak in Europe (Italy)	Natural	24.02.2020	https://www.cdc.gov/museum/timeline/covid19.html
20	Protocol on Ireland/Northern Ireland	Geopolitical	21.09.2021	Timeline - The EU-UK withdrawal agreement - Consilium (europa.eu)
21	40-year record inflation release	Economic	12 01 2022	https://www.bls.gov/news.release/archives/cpi_01122022.pdf
21	FFD raises raised interest rates by largest hike over 20 years	Economic	04 05 2022	$\frac{1}{1}$
22	Enormy and inflation arisis in Europa	Geopolitical	00.08.2022	https://www.bis.org/pub//upu//_upu//_upa/https://solatile
23	Energy and miliation crisis in Europe	Geopolitical	09.00.2022	week-followed-up-by-big-macro-week/

Note: This table presents sources confirming the dates of specific events. The dates were endogenously chosen by the bootstrap-after-bootstrap procedure created by Greenwood-Nimmo et al. (2024). The dataset encompasses the period from September 27, 2009, to April 30, 2023, and we calculate the daily variances using data at one-minute intervals.

	USD/AUD	USD/CAD	USD/EUR	USD/GBP	USD/CHF	USD/JPY	USD/NZD	USD/CNY	USD/HKD	FROM Others
USD/AUD	97,59	0,41	0,19	0,47	0,02	0,09	1,27	0,00	0,02	2,29
USD/CAD	0,24	49,63	3,62	8,89	0,53	19,54	17,75	0,07	0,22	50,37
USD/EUR	0,14	4,38	74,47	6,51	1,93	1,61	10,02	0,12	0,26	25,53
USD/GBP	0,32	9,92	4,53	68,68	0,45	6,34	9,78	0,02	0,10	31,32
USD/CHF	0,02	1,05	2,03	0,76	93,15	0,44	2,29	0,02	0,02	6,58
USD/JPY	0,06	25,27	1,48	6,97	0,27	61,64	4,78	0,01	0,06	38,36
USD/NZD	0,64	17,02	6,63	7,81	1,03	3,22	63,28	0,21	0,05	36,72
USD/CNY	0,01	0,11	0,14	0,03	0,01	0,00	0,30	99,38	0,01	0,62
USD/HKD	0,02	0,31	0,21	0,07	0,02	0,07	0,02	0,01	99,28	0,73
TO Others	1,61	58,97	18,43	31,61	4,15	31,43	45,68	0,47	0,73	
NET Spil l oved										
STILLOVER	-0,97	8,92	-7,10	0,29	-2,70	-6,93	8,29	-0,15	0,01	

 Table A3: Volatility spillover table

Note: The values in the table represent the percentage of volatility shared between currencies. Column "FROM" demonstrates volatility received from other currencies; row "TO" demonstrates volatility transmitted to other currencies. In the row "NET SPILLOVER", we compare received and transmitted volatility. The dataset encompasses the period from September 27, 2009, to April 30, 2023, and we calculate the daily variances using data at one-minute intervals. The static volatility spillover table is calculated based on $\frac{\theta^{g}_{e}(H)}{\theta^{g}_{e}(H)}$

modifications of specification (2): $S_{i\leftarrow j}^{H} = \frac{\theta_{i,j}^{g}(H)}{\sum_{j=1}^{N} \theta_{i,j}^{g}(H)}$ for spillovers FROM variable(s), $S_{i\rightarrow j}^{H} = \frac{\theta_{i,j}^{g}(H)}{\sum_{j=1}^{N} \theta_{i,j}^{g}(H)}$ for spillovers TO variable(s), and $S_{N,i}^{H} = S_{i\rightarrow j}^{H} - S_{i\leftarrow j}^{H}$, for net spillovers.

		r _e -1		r _e -5		r _e -10		r _e -22	
Event	Description of the shock	OVD	GVD	OVD	GVD	OVD	GVD	OVD	GVD
1	The US debt ceiling increased	48,20	46,60	48,20	44,90	51,30	52,00	43,20	46,30
2	ECB LTRO announcement	49,30	49,90	44,00	48,20	50,40	50,70	50,90	52,20
3	Greece election	41,60	43,60	56,90	40,50	54,10	59,00	54,20	49,70
4	The US approaches a "fiscal cliff"	52,20	50,30	52,90	51,30	49,60	48,00	47,60	43,80
5	Bank of Japan intervenes	49,50	44,10	56,50	44,30	53,90	40,10	56,80	47,40
6	Greek Parliament Approves Austerity Measures	68,70	55,20	48,10	40,60	50,30	47,80	48,60	42,70
7	Debate before US government shutdown intensified	48,00	47,10	49,80	40,60	49,30	46,10	45,40	45,40
8	Crimea referendum	49,30	47,10	46,80	49,00	46,60	44,20	48,70	51,50
9	Minsk protocol	44,80	46,40	42,70	40,70	47,20	46,80	46,20	45,50
10	Weak US jobs pushed back expectations of a US rate hike	45,60	47,40	46,20	44,20	47,30	46,30	50,80	51,10
11	BREXIT referendum	48,60	48,80	53,00	49,20	45,50	47,00	45,90	47,60
12	Draft guidelines for negotiations about BREXIT	57,50	52,40	47,10	47,80	46,80	46,00	49,30	49,70
13	North Korea fires missile over Japan	50,00	51,30	45,50	45,40	56,20	55,50	43,20	42,20
14	Advancement in Brexit negotiations	45,70	42,60	49,00	48,70	53,00	51,50	47,40	50,40
15	US implements first China-specific tariffs	49,70	46,80	51,00	54,20	43,80	43,80	51,80	52,50
16	US government partial shutdown	39,50	37,50	86,50	55,50	51,90	48,60	44,30	51,20
17	US exempts 110 Chinese products from 25 percent tariffs	45,50	52,60	55,30	50,60	51,50	50,60	46,90	42,30
18	New regulatory guidelines regarding trade war with China	52,80	49,70	47,20	44,80	50,50	50,00	55,50	52,30
19	Covid outbreak in Europe (Italy)	43,00	45,20	29,50	44,50	53,70	52,60	50,00	56,10
20	Protocol on Ireland/Northern Ireland	46,80	41,70	48,60	49,20	51,10	50,50	46,20	43,90
21	40-year record inflation release	55,10	51,90	47,80	49,70	51,50	47,10	45,10	45,60
22	FED raises raised interest rates by largest hike over 20 years	45,80	45,30	48,40	49,20	47,40	48,10	51,40	55,10
23	Energy and inflation crisis in Europe	48,30	45,40	59,20	54,90	48,30	47,30	53,80	52,30

Table A4: Empirical Probability of an Increase in Connectedness before Selected Events, in Percent

Note: the table presents the empirical likelihood of the connectedness index surpassing the mean of the connectedness index over the specified r_{e^-j} days. We employed a rolling sample approach using bootstrap samples to obtain these results. Under the "OVD" and "GVD" headings, the indicated probabilities correspond to the connectedness indices calculated using orthogonalized and generalized forecast error variance decompositions. To generate these probabilities, we followed the methodology employed by Greenwood-Nimmo et al. (2024) and conducted 1000 non-parametric replications using the bootstrap-after-bootstrap technique. The reported results pertain to the following currency pairs: USD/AUD, USD/CAD, USD/CHF, USD/GBP, USD/CHF, USD/JPY, USD/NZD, USD/CNY, and USD/HKD. The dataset encompasses the period from September 27, 2009, to April 30, 2023, and we calculate the daily variances using data at one-minute intervals. The probabilities of association between a shock and an increase in connectedness are calculated based on specification (4): $Prob\left(100 \times \left[\frac{S_{t+i}-\tilde{S}_{t-j}}{\bar{S}_{t-j}}\right] > \alpha\right), i \in \{0,1, ...\}, j \in \{1,2, ...\}.$

Event	Description of the shock	r	e+0	re	+1	re	+5	r _e +	10	r _e +2	22
		OVD	GVD	OVD	GVD	OVD	GVD	OVD	GVD	OVD	GVD
1	The US debt ceiling increased	45,80	41,70	44,50	47,80	85,70	79,90	48,40	66,00	31,40	48,10
2	ECB LTRO announcement	46,90	44,90	49,70	45,00	49,50	43,70	89,40	73,20	82,40	64,60
3	Greece election	50,50	45,40	48,50	44,30	32,30	75,40	71,70	84,70	51,10	95,70
4	The US approaches a "fiscal cliff"	52,70	54.30	52.50	51,80	56,70	48,70	64.50	58,50	100.00	57,40
5	Bank of Japan intervenes	99.90	100.00	79.00	91.00	4.40	15.20	5.00	16.30	3.50	11.20
6	Greek Parliament Approves Austerity		,	,		.,	,	-,	,	- ,	,-•
-	Measures	48,20	65,30	48,60	71,90	46,50	65,00	44,80	68,30	50,80	95,20
/	intensified	77.30	99.70	81.20	99.50	5.80	99.50	12.90	99.60	10.20	99.60
8	Crimea referendum	48 40	48 20	50.40	46 70	62 40	44 00	75.80	43.80	93.80	97.30
9	Minsk protocol	45 20	41.90	44 20	44 50	38.90	47.40	40.40	47.60	7 20	92.70
10	Weak US jobs pushed back expectations of a	13,20	11,90	11,20	11,50	50,90	17,10	10,10	17,00	7,20	,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,
	US rate hike	48,70	45,50	46,70	47,70	42,70	47,00	53,90	53,10	93,80	100,00
11	BREXIT referendum	78,70	92,70	92,30	98,80	92,20	97,40	87,90	96,90	82,80	96,40
12	Draft guidelines for negotiations about	21.20	20.50	24.50	24.20	42.00	22.20	52 10	24.20	(7.90	(0.00
13	BREAH North Korea fires missile over Japan	51,50	20,50	34,50	24,50	45,90	32,20	52,10	54,20	07,80	60,90
14	Advancement in Brexit pegotiations	50,10	48,50	49,10	49,10	/1,60	21,80	58,50	46,30	79,20	87,30
15	US implements first China-specific tariffs	58,80	61,70	60,40	57,70	59,10	61,00	60,30	58,40	99,40	95,80
15	US asymmet partial shutdown	74,60	97,70	76,00	98,40	83,80	97,20	83,90	98,30	84,70	97,80
10	US government partial shutdown	44,80	34,90	100,00	100,00	99,80	86,60	99,80	80,40	100,00	76,80
17	US exempts 110 Chinese products from 25 percent tariffs	55,10	64,00	53,90	61,70	64,80	75,10	66,20	76,70	81,90	95,30
18	New regulatory guidelines regarding trade war	54.00	57.50	55.00	54.50	57.50	(2.20	((10	92 (0	91.20	02.00
19	Covid outbreak in Europe (Italy)	34,00 42,20	57,50	35,90	54,50 42,70	37,30	03,20	00,10	82,00	01,20 100.00	92,00
2.0	Protocol on Ireland/Northern Ireland	43,20	45,00	45,00	43,70	86,00	93,40	97,90	98,60	100,00	100,00
20	40-year record inflation release	54,80	43,20	52,60	43,50	75,90	71,20	81,60	96,40	79,10	89,10
21 22	EED raises raised interest rates by laws of hills	49,50	50,80	55,20	49,40	54,90	52,50	97,20	99,90	98,40	100,00
<i>LL</i>	over 20 years	70,30	67,50	71,50	77,20	93,60	95,60	94,90	95,90	94,70	95,40
23	Energy and inflation crisis in Europe	56,00	55,60	97,80	98,40	84,00	74,50	27,90	40,90	27,80	43,60

 Table A5: Robustness of the Empirical Probabilities for the use of a 5-day Average as a Pre-Event Comparator, in Percent

Note: the table presents the empirical likelihood of the connectedness index surpassing the mean of the connectedness index over the specified r_e+j days. We employed a rolling sample approach using bootstrap samples to obtain these results. Under the "OVD" and "GVD" headings, the indicated probabilities correspond to the connectedness indices calculated using orthogonalized and generalized forecast error variance decompositions. To generate these probabilities, we followed the methodology employed by Greenwood-Nimmo et al. (2024) and conducted 1000 non-parametric replications using the bootstrap-after-bootstrap technique. The reported results pertain to the following currency pairs: USD/AUD, USD/CAD, USD/EUR, USD/GBP, USD/CHF, USD/JPY, USD/NZD, USD/CNY, and USD/HKD. The dataset encompasses the period from September 27, 2009, to April 30, 2023, and we calculate the daily variances using data at one-minute intervals. The probabilities of association between a shock and an increase in connectedness are calculated based on specification (4): $Prob\left(100 \times \left[\frac{S_{t+i}-\bar{S}_{t-j}}{\bar{S}_{t-j}}\right] > \alpha\right), i \in \{0,1, ...\}, j \in \{1,2, ...\}.$

					EU debt	t crisis				
		H	edge ratios				Р	ortfolio we	eights	
Currencies	Mean	Median	sd	Min	Max	Mean	Median	sd	Min	Max
CHF - CAD	0.44	0.43	0.07	0.26	0.63	0.54	0.57	0.15	0.13	0.77
GBP - CAD	0.43	0.43	0.09	0.19	0.67	0.54	0.55	0.17	0.17	0.92
AUD - CAD	0.80	0.78	0.15	0.42	1.19	0.20	0.20	0.17	-0.07	0.75
EUR - CAD	0.44	0.45	0.07	0.22	0.69	0.62	0.62	0.13	0.22	0.90
JPY - CAD	0.53	0.53	0.16	0.27	0.95	0.34	0.29	0.23	0.01	0.78
NZD - CAD	0.77	0.76	0.15	0.34	1.17	0.18	0.16	0.15	-0.04	0.69
CNY - CAD	0.01	0.01	0.00	0.00	0.02	1.01	1.00	0.00	1.00	1.01
HKD - CAD	0.00	0.00	0.01	-0.01	0.03	0.99	0.99	0.02	0.88	1.00
CAD - CHF	0.47	0.50	0.10	0.20	0.62					
GBP - CHF	0.48	0.47	0.12	0.30	0.85	0.51	0.49	0.19	0.07	0.80
AUD - CHF	0.67	0.67	0.14	0.30	1.03	0.23	0.21	0.13	-0.01	0.65
EUR - CHF	0.80	0.83	0.11	0.48	1.02	0.78	0.72	0.4	-0.06	1.48
JPY - CHF	0.61	0.59	0.16	0.35	0.98	0.29	0.27	0.19	0.00	0.72
NZD - CHF	0.61	0.63	0.16	0.19	0.98	0.22	0.18	0.15	0.01	0.66
CNY - CHF	0.00	0.00	0.00	0.00	0.01	1.00	1.00	0.00	0.99	1.00
HKD - CHF	0.01	0.02	0.01	0.00	0.06	1.00	1.00	0.01	0.92	1.01
CAD - GBP	0.47	0.48	0.10	0.26	0.73					
CHF - GBP	0.49	0.49	0.10	0.24	0.69					
AUD - GBP	0.61	0.63	0.15	0.28	0.95	0.25	0.19	0.17	0.01	0.73
EUR - GBP	0.47	0.48	0.10	0.25	0.79	0.58	0.59	0.18	0.12	0.97
JPY - GBP	0.51	0.47	0.18	0.20	1.07	0.32	0.31	0.20	-0.01	0.69
NZD - GBP	0.78	0.77	0.21	0.36	1.27	0.18	0.14	0.20	-0.05	0.74
CNY - GBP	0.00	0.00	0.00	0.00	0.01	0.99	1.00	0.00	0.99	1.00
HKD - GBP	0.01	0.01	0.01	0.00	0.08	0.99	1.00	0.02	0.84	1.01
CAD - AUD	0.46	0.47	0.08	0.30	0.73					
CHF - AUD	0.36	0.35	0.05	0.22	0.56					
GBP - AUD	0.32	0.30	0.07	0.18	0.51					
EUR - AUD	0.36	0.35	0.07	0.22	0.66	0.87	0.86	0.13	0.25	1.08
JPY - AUD	0.52	0.51	0.12	0.31	0.79	0.54	0.56	0.22	0.12	0.97
NZD - AUD	0.85	0.86	0.08	0.66	1.04	0.32	0.28	0.19	-0.04	0.80
CNY - AUD	0.00	0.00	0.00	0.00	0.01	1.00	1.00	0.00	1.00	1.00
HKD - AUD	0.01	0.00	0.01	0.00	0.04	1.00	1.00	0.01	0.96	1.01
CAD - EUR	0.57	0.57	0.09	0.38	0.81					
CHF - EUR	0.97	0.93	0.15	0.77	1.54					
GBP - EUR	0.56	0.56	0.12	0.28	0.92					
AUD - EUR	0.82	0.79	0.15	0.40	1.33					
JPY - EUR	0.65	0.60	0.19	0.28	1.15	0.24	0.22	0.18	-0.03	0.79
NZD - EUR	0.82	0.81	0.18	0.40	1.34	0.12	0.10	0.13	-0.06	0.73
CNY - EUR	0.00	0.00	0.00	0.00	0.01	1.00	1.00	0.00	0.99	1.01
HKD - EUR	0.02	0.02	0.02	0.00	0.08	1.00	1.00	0.02	0.87	1.01
CAD - JPY	0.34	0.31	0.12	0.19	0.61					

Table A6: Hedge ratios and portfolio weights – EU Debt crisis period

CHF - JPY	0.36	0.34	0.09	0.17	0.58					
GBP - JPY	0.29	0.27	0.08	0.15	0.45					
AUD - JPY	0.57	0.55	0.14	0.34	0.93					
EUR - JPY	0.32	0.29	0.09	0.19	0.60					
NZD - JPY	0.50	0.46	0.16	0.24	0.88	0.41	0.43	0.19	0.04	0.81
CNY - JPY	0.00	0.00	0.00	-0.01	0.00	0.99	0.99	0.00	0.99	1.00
HKD - JPY	0.00	0.00	0.00	0.00	0.02	0.99	1.00	0.01	0.95	1.00
CAD - NZD	0.37	0.37	0.07	0.22	0.61					
CHF - NZD	0.27	0.27	0.05	0.17	0.49					
GBP - NZD	0.35	0.34	0.10	0.20	0.62					
AUD - NZD	0.73	0.73	0.06	0.53	0.89					
EUR - NZD	0.31	0.31	0.07	0.18	0.65					
JPY - NZD	0.38	0.38	0.09	0.19	0.58					
CNY - NZD	0.00	0.00	0.00	0.00	0.01	1.00	1.00	0.00	1.00	1.00
HKD - NZD	0.00	0.00	0.00	-0.01	0.01	0.99	0.99	0.01	0.95	1.00
CAD - CNY	2.25	2.17	0.63	1.25	4.31					
CHF - CNY	0.48	0.43	0.37	-0.45	1.68					
GBP - CNY	0.06	0.09	0.41	-1.05	1.39					
AUD - CNY	1.47	1.52	0.69	-0.63	3.20					
EUR - CNY	0.71	0.60	0.45	-0.14	2.06					
JPY - CNY	-1.02	-0.80	0.58	-3.18	0.29					
NZD - CNY	1.27	1.29	0.68	-0.60	3.12					
HKD - CNY	-0.29	-0.27	0.29	-1.58	-0.03	0.54	0.44	0.30	0.09	0.95
CAD - HKD	0.22	0.16	1.87	-3.52	6.94					
CHF - HKD	5.83	1.87	6.96	0.37	28.55					
GBP - HKD	3.99	1.50	5.03	0.28	21.60					
AUD - HKD	3.26	1.41	4.26	-0.26	19.23					
EUR - HKD	6.22	1.84	7.53	0.37	30.91					
JPY - HKD	1.54	0.50	2.25	-0.69	9.64					
NZD - HKD	-2.57	-0.68	4.21	-13.95	2.22					
CNY - HKD	-0.50	-0.19	0.50	-1.69	-0.06					

					Greece l	oailout				
		H	edge ratios				Р	ortfolio we	ights	
Currencies	Mean	Median	sd	Min	Max	Mean	Median	sd	Min	Max
CHF - CAD	0.26	0.26	0.07	0.12	0.78	0.51	0.48	0.18	0.03	0.91
GBP - CAD	0.36	0.36	0.07	0.23	0.62	0.69	0.70	0.14	0.23	1.00
AUD - CAD	0.83	0.80	0.16	0.56	1.21	0.25	0.25	0.23	-0.13	0.74
EUR - CAD	0.45	0.45	0.09	0.24	0.72	0.50	0.48	0.18	0.14	0.92
JPY - CAD	0.37	0.36	0.11	0.20	0.86	0.45	0.45	0.18	0.07	0.82
NZD - CAD	0.66	0.66	0.13	0.44	1.12	0.35	0.33	0.19	-0.04	0.78
CNY - CAD	0.01	0.01	0.01	0.00	0.03	0.95	0.98	0.05	0.80	1.00
HKD - CAD	0.01	0.01	0.01	0.00	0.05	0.99	1.00	0.01	0.95	1.01
CAD - CHF	0.27	0.25	0.10	0.10	0.61					
GBP - CHF	0.24	0.22	0.09	0.12	0.57	0.64	0.66	0.17	0.12	0.94
AUD - CHF	0.33	0.29	0.16	0.10	0.99	0.39	0.40	0.20	0.00	0.83
EUR - CHF	0.37	0.36	0.09	0.19	0.70	0.49	0.50	0.14	0.10	0.86
JPY - CHF	0.38	0.33	0.17	0.21	1.10	0.46	0.50	0.21	-0.01	0.86
NZD - CHF	0.36	0.35	0.14	0.15	0.96	0.40	0.42	0.18	0.01	0.80
CNY - CHF	0.02	0.01	0.01	0.00	0.05	0.96	0.98	0.05	0.82	1.00
HKD - CHF	0.00	0.00	0.00	-0.03	0.01	0.97	0.99	0.03	0.81	1.00
CAD - GBP	0.58	0.57	0.11	0.32	0.99					
CHF - GBP	0.37	0.36	0.09	0.16	0.68					
AUD - GBP	0.67	0.65	0.15	0.29	1.18	0.19	0.18	0.13	-0.03	0.69
EUR - GBP	0.61	0.61	0.10	0.37	0.84	0.30	0.27	0.15	0.07	0.82
JPY - GBP	0.43	0.40	0.15	0.21	1.17	0.31	0.32	0.15	-0.04	0.67
NZD - GBP	0.64	0.63	0.12	0.38	1.11	0.21	0.19	0.12	-0.03	0.70
CNY - GBP	0.03	0.03	0.01	0.00	0.06	0.94	0.97	0.07	0.70	1.00
HKD - GBP	0.02	0.02	0.01	0.01	0.07	0.99	1.00	0.03	0.82	1.02
CAD - AUD	0.56	0.57	0.10	0.36	0.81					
CHF - AUD	0.21	0.21	0.07	0.08	0.41					
GBP - AUD	0.29	0.28	0.06	0.14	0.54					
EUR - AUD	0.43	0.44	0.11	0.19	0.71	0.66	0.64	0.22	0.20	1.05
JPY - AUD	0.32	0.32	0.11	0.13	0.78	0.57	0.59	0.22	0.09	0.96
NZD - AUD	0.69	0.68	0.12	0.43	1.11	0.58	0.60	0.27	-0.10	1.13
CNY - AUD	0.00	0.00	0.01	-0.04	0.02	0.96	0.98	0.04	0.78	1.00
HKD - AUD	0.01	0.01	0.00	0.00	0.02	0.99	1.00	0.01	0.94	1.01
CAD - EUR	0.46	0.43	0.11	0.25	0.83					
CHF - EUR	0.35	0.35	0.07	0.21	0.62					
GBP - EUR	0.39	0.38	0.08	0.26	0.73					
AUD - EUR	0.65	0.59	0.20	0.33	1.25					
JPY - EUR	0.25	0.23	0.10	0.10	0.84	0.46	0.48	0.16	0.03	0.85
NZD - EUR	0.56	0.53	0.14	0.30	0.92	0.38	0.39	0.18	0.02	0.80
CNY - EUR	0.00	0.00	0.01	-0.04	0.03	0.94	0.96	0.05	0.80	0.99
HKD - EUR	0.01	0.01	0.01	-0.01	0.03	0.99	0.99	0.02	0.84	1.00
CAD - JPY	0.32	0.32	0.09	0.07	0.54					

Table A7: Hedge ratios and portfolio weights – Greece bailout period

	-									
CHF - JPY	0.32	0.32	0.11	0.08	0.62					
GBP - JPY	0.23	0.23	0.06	0.07	0.34					
AUD - JPY	0.41	0.38	0.14	0.09	0.80					
EUR - JPY	0.21	0.22	0.06	0.04	0.37					
NZD - JPY	0.36	0.37	0.12	0.05	0.67	0.45	0.43	0.21	0.08	0.96
CNY - JPY	0.02	0.02	0.01	-0.01	0.08	0.97	0.98	0.04	0.81	1.01
HKD - JPY	0.00	0.00	0.00	-0.01	0.01	0.98	0.99	0.02	0.86	1.00
CAD - NZD	0.49	0.48	0.09	0.27	0.79					
CHF - NZD	0.26	0.26	0.07	0.11	0.46					
GBP - NZD	0.30	0.30	0.06	0.20	0.60					
AUD - NZD	0.76	0.76	0.14	0.49	1.15					
EUR - NZD	0.41	0.41	0.08	0.24	0.66					
JPY - NZD	0.31	0.29	0.12	0.15	0.87					
CNY - NZD	0.00	0.00	0.01	-0.03	0.02	0.96	0.98	0.05	0.79	1.00
HKD - NZD	0.02	0.02	0.01	0.00	0.04	1.00	1.01	0.01	0.95	1.01
CAD - CNY	0.35	0.35	0.21	-0.01	0.94					
CHF - CNY	0.38	0.36	0.24	-0.05	1.21					
GBP - CNY	0.40	0.39	0.19	0.02	0.83					
AUD - CNY	0.12	0.15	0.33	-1.12	0.65					
EUR - CNY	-0.11	-0.06	0.23	-0.94	0.34					
JPY - CNY	0.65	0.57	0.33	-0.03	1.42					
NZD - CNY	0.16	0.17	0.28	-0.79	1.06					
HKD - CNY	-0.02	-0.01	0.04	-0.19	0.10	0.67	0.75	0.25	0.09	0.97
CAD - HKD	0.94	0.85	0.53	0.14	3.35					
CHF - HKD	-0.19	-0.21	0.21	-0.82	0.43					
GBP - HKD	0.97	0.90	0.45	0.15	2.54					
AUD - HKD	0.73	0.71	0.53	-0.33	3.27					
EUR - HKD	0.46	0.46	0.30	-0.18	1.68					
JPY - HKD	0.23	0.17	0.43	-1.68	2.79					
NZD - HKD	1.52	1.45	0.68	0.26	3.29					
CNY - HKD	-0.02	-0.03	0.06	-0.21	0.20					

	US Debt Ceiling											
		H	edge ratios				Р	ortfolio we	eights			
Currencies	Mean	Median	sd	Min	Max	Mean	Median	sd	Min	Max		
CHF - CAD	0.58	0.54	0.33	-0.01	4.04	0.32	0.31	0.19	-0.05	0.90		
GBP - CAD	0.44	0.43	0.16	0.14	3.96	0.53	0.50	0.20	-0.13	1.04		
AUD - CAD	0.85	0.85	0.19	0.38	1.66	0.15	0.11	0.19	-0.30	0.90		
EUR - CAD	0.61	0.58	0.20	0.18	1.38	0.34	0.32	0.22	-0.24	0.98		
JPY - CAD	0.39	0.36	0.20	-0.31	1.89	0.34	0.31	0.20	-0.19	0.95		
NZD - CAD	0.48	0.36	0.77	0.12	11.8	0.26	0.24	0.15	-0.01	0.79		
CNY - CAD	0.03	0.03	0.04	-0.14	0.20	0.87	0.91	0.13	0.27	1.01		
HKD - CAD	0.02	0.01	0.03	-0.04	0.21	1.00	1.01	0.03	0.62	1.09		
CAD - CHF	0.33	0.33	0.11	-0.01	0.75							
GBP - CHF	0.36	0.36	0.16	0.07	4.28	0.71	0.72	0.20	-0.10	1.09		
AUD - CHF	0.49	0.48	0.16	0.05	1.36	0.43	0.42	0.20	-0.20	1.06		
EUR - CHF	0.80	0.81	0.19	0.13	1.76	0.56	0.58	0.39	-0.77	1.35		
JPY - CHF	0.34	0.32	0.18	0.01	2.04	0.47	0.47	0.24	-0.16	1.02		
NZD - CHF	0.32	0.25	0.53	0.05	7.26	0.39	0.38	0.17	-0.01	0.98		
CNY - CHF	0.00	0.01	0.03	-0.17	0.08	0.90	0.93	0.10	0.48	1.02		
HKD - CHF	0.01	0.01	0.02	-0.03	0.12	0.99	1.00	0.05	0.45	1.05		
CAD - GBP	0.47	0.44	0.16	0.13	1.18							
CHF - GBP	0.67	0.61	0.42	0.11	4.47							
AUD - GBP	0.70	0.66	0.24	0.25	1.63	0.22	0.20	0.18	-0.16	1.27		
EUR - GBP	0.68	0.67	0.22	0.13	1.67	0.30	0.26	0.23	-0.09	1.35		
JPY - GBP	0.50	0.47	0.21	0.10	1.92	0.31	0.30	0.19	-0.05	1.36		
NZD - GBP	0.29	0.27	0.14	-0.47	1.01	0.26	0.24	0.14	0.00	1.05		
CNY - GBP	0.02	0.02	0.04	-0.26	0.13	0.85	0.89	0.14	0.21	1.01		
HKD - GBP	0.02	0.01	0.03	-0.05	0.30	0.99	1.00	0.04	0.55	1.06		
CAD - AUD	0.44	0.43	0.10	0.17	0.88							
CHF - AUD	0.42	0.40	0.19	0.04	2.22							
GBP - AUD	0.33	0.33	0.12	0.08	2.77							
EUR - AUD	0.43	0.42	0.13	0.08	0.92	0.62	0.63	0.23	0.04	1.10		
JPY - AUD	0.34	0.34	0.15	0.05	1.27	0.54	0.55	0.22	-0.23	1.01		
NZD - AUD	0.35	0.30	0.30	0.10	3.43	0.43	0.44	0.15	-0.01	0.86		
CNY - AUD	0.02	0.02	0.03	-0.08	0.18	0.92	0.95	0.09	0.43	1.02		
HKD - AUD	0.01	0.01	0.02	-0.03	0.18	1.00	1.00	0.03	0.67	1.06		
CAD - EUR	0.41	0.41	0.13	0.07	0.93							
CHF - EUR	0.91	0.86	0.37	0.20	4.90							
GBP - EUR	0.43	0.42	0.14	0.14	2.72							
AUD - EUR	0.57	0.54	0.20	0.07	1.22							
JPY - EUR	0.40	0.36	0.21	0.04	1.26	0.45	0.45	0.26	-0.24	1.00		
NZD - EUR	0.39	0.28	0.68	0.04	9.00	0.36	0.36	0.18	-0.01	0.89		
CNY - EUR	0.00	0.00	0.04	-0.23	0.11	0.88	0.92	0.10	0.42	1.02		
HKD - EUR	0.01	0.01	0.02	-0.02	0.12	0.99	1.00	0.05	0.48	1.06		
CAD - JPY	0.23	0.22	0.11	-0.02	0.73							

Table A8: Hedge ratios and portfolio weights – US Debt ceiling period

	_									
CHF - JPY	0.33	0.30	0.22	0.03	1.88					
GBP - JPY	0.27	0.26	0.11	0.03	1.64					
AUD - JPY	0.39	0.38	0.17	0.04	1.06					
EUR - JPY	0.33	0.32	0.15	0.03	1.00					
NZD - JPY	0.12	0.14	0.32	-5.11	0.43	0.41	0.39	0.19	0.00	0.95
CNY - JPY	0.00	0.00	0.03	-0.17	0.09	0.90	0.93	0.10	0.37	1.01
HKD - JPY	0.01	0.00	0.01	-0.06	0.06	0.99	1.00	0.04	0.51	1.02
CAD - NZD	0.16	0.15	0.06	0.00	0.35					
CHF - NZD	0.17	0.16	0.07	0.01	0.69					
GBP - NZD	0.11	0.11	0.06	0.00	1.56					
AUD - NZD	0.25	0.26	0.07	0.00	0.51					
EUR - NZD	0.18	0.18	0.07	0.01	0.54					
JPY - NZD	0.11	0.10	0.06	-0.01	0.71					
CNY - NZD	0.02	0.02	0.01	-0.01	0.06	0.94	0.96	0.07	0.56	1.01
HKD - NZD	0.00	0.00	0.01	-0.01	0.05	0.99	1.00	0.03	0.59	1.02
CAD - CNY	0.23	0.17	0.30	-0.56	1.85					
CHF - CNY	0.09	0.06	0.53	-4.84	1.68					
GBP - CNY	0.19	0.14	0.30	-0.45	5.23					
AUD - CNY	0.36	0.24	0.48	-0.64	2.22					
EUR - CNY	0.01	-0.02	0.40	-1.63	1.68					
JPY - CNY	0.06	0.03	0.40	-3.39	2.33					
NZD - CNY	0.52	0.28	1.33	-0.10	16.43					
HKD - CNY	0.05	0.03	0.05	-0.18	0.44	0.93	0.99	0.15	0.12	1.13
CAD - HKD	2.68	2.02	2.24	-1.18	9.60					
CHF - HKD	2.81	2.12	2.57	-0.92	11.21					
GBP - HKD	2.07	1.47	1.87	-0.90	20.80					
AUD - HKD	3.07	2.34	2.95	-2.25	11.65					
EUR - HKD	2.59	1.91	2.33	-0.85	9.84					
JPY - HKD	1.98	1.40	2.11	-0.94	15.26					
NZD - HKD	1.85	1.13	3.28	-0.87	38.34					
CNY - HKD	0.92	0.73	0.78	-0.32	4.78					

	Brexit referendum											
		Н	edge ratios				Р	ortfolio we	ights			
Currencies	Mean	Median	sd	Min	Max	Mean	Median	sd	Min	Max		
CHF - CAD	0.33	0.32	0.14	0.03	1.23	0.52	0.53	0.20	-0.16	0.98		
GBP - CAD	0.23	0.22	0.12	-0.04	0.99	0.35	0.33	0.15	0.00	0.84		
AUD - CAD	0.51	0.51	0.15	0.04	1.16	0.39	0.37	0.20	-0.10	0.95		
EUR - CAD	0.39	0.36	0.19	0.00	1.44	0.50	0.51	0.20	-0.27	0.90		
JPY - CAD	0.49	0.43	0.27	0.02	1.81	0.37	0.38	0.24	-0.26	0.99		
NZD - CAD	0.44	0.43	0.12	0.18	1.05	0.38	0.37	0.17	0.00	0.86		
CNY - CAD	0.01	0.01	0.04	-0.15	0.18	0.66	0.67	0.15	0.19	0.96		
HKD - CAD	-0.03	-0.02	0.02	-0.22	0.00	0.94	0.96	0.06	0.50	0.99		
CAD - CHF	0.35	0.34	0.11	0.12	0.77							
GBP - CHF	0.34	0.33	0.13	0.06	1.04	0.32	0.31	0.17	0.00	0.93		
AUD - CHF	0.42	0.40	0.11	0.17	0.91	0.39	0.38	0.16	0.02	1.02		
EUR - CHF	0.69	0.67	0.17	0.33	1.34	0.45	0.43	0.27	-0.24	1.12		
JPY - CHF	0.69	0.66	0.24	0.24	1.75	0.29	0.26	0.25	-0.36	1.04		
NZD - CHF	0.40	0.39	0.13	0.13	1.28	0.36	0.33	0.18	-0.03	1.00		
CNY - CHF	-0.01	-0.01	0.05	-0.30	0.12	0.64	0.66	0.15	0.12	0.96		
HKD - CHF	-0.01	0.00	0.01	-0.15	0.03	0.95	0.97	0.05	0.47	1.00		
CAD - GBP	0.13	0.13	0.06	-0.12	0.35							
CHF - GBP	0.18	0.17	0.08	0.03	0.77							
AUD - GBP	0.22	0.21	0.08	0.05	0.69	0.59	0.59	0.16	0.09	1.00		
EUR - GBP	0.23	0.22	0.10	0.05	0.87	0.66	0.68	0.19	0.03	1.01		
JPY - GBP	0.25	0.23	0.12	0.04	1.18	0.55	0.58	0.19	-0.02	0.95		
NZD - GBP	0.19	0.19	0.07	0.03	0.45	0.56	0.55	0.16	0.09	0.96		
CNY - GBP	0.01	0.01	0.04	-0.20	0.12	0.77	0.80	0.14	0.26	0.99		
HKD - GBP	-0.01	-0.01	0.01	-0.07	0.04	0.96	0.98	0.04	0.76	1.00		
CAD - AUD	0.38	0.38	0.11	0.13	0.84							
CHF - AUD	0.31	0.30	0.11	0.07	1.12							
GBP - AUD	0.29	0.27	0.12	0.08	0.98							
EUR - AUD	0.39	0.38	0.13	0.12	1.12	0.60	0.61	0.20	-0.13	1.01		
JPY - AUD	0.43	0.40	0.18	0.10	1.35	0.45	0.48	0.22	-0.21	0.89		
NZD - AUD	0.64	0.63	0.14	0.37	1.44	0.46	0.44	0.24	-0.20	1.03		
CNY - AUD	0.03	0.03	0.04	-0.04	0.20	0.72	0.74	0.14	0.25	0.96		
HKD - AUD	-0.02	-0.01	0.02	-0.14	0.01	0.95	0.97	0.05	0.64	1.00		
CAD - EUR	0.37	0.36	0.10	-0.02	0.71							
CHF - EUR	0.64	0.63	0.15	0.19	1.22							
GBP - EUR	0.40	0.38	0.15	0.13	1.12							
AUD - EUR	0.50	0.51	0.14	0.21	1.05							
JPY - EUR	0.59	0.54	0.23	0.15	1.59	0.35	0.35	0.24	-0.37	0.93		
NZD - EUR	0.42	0.41	0.12	0.14	1.13	0.38	0.37	0.18	-0.01	1.04		
CNY - EUR	0.00	-0.01	0.04	-0.20	0.15	0.66	0.68	0.16	0.15	0.97		
HKD - EUR	-0.02	-0.02	0.02	-0.11	0.01	0.93	0.96	0.08	0.44	0.99		
CAD - JPY	0.31	0.30	0.11	0.07	0.96							

Table A9: Hedge ratios and portfolio weights – Brexit referendum period

	-									
CHF - JPY	0.43	0.42	0.13	0.14	1.09					
GBP - JPY	0.28	0.28	0.09	0.04	0.65					
AUD - JPY	0.37	0.36	0.10	0.16	0.71					
EUR - JPY	0.40	0.39	0.13	0.11	0.81					
NZD - JPY	0.35	0.34	0.11	0.16	0.89	0.52	0.50	0.21	0.02	1.07
CNY - JPY	-0.02	-0.01	0.05	-0.29	0.17	0.72	0.75	0.16	0.23	0.98
HKD - JPY	-0.02	-0.01	0.02	-0.13	0.01	0.95	0.97	0.05	0.64	1.00
CAD - NZD	0.32	0.31	0.10	0.07	0.70					
CHF - NZD	0.26	0.25	0.09	0.06	0.99					
GBP - NZD	0.24	0.23	0.10	0.01	0.73					
AUD - NZD	0.59	0.58	0.15	0.17	1.04					
EUR - NZD	0.30	0.29	0.11	0.04	1.15					
JPY - NZD	0.38	0.34	0.17	0.05	1.50					
CNY - NZD	0.05	0.04	0.04	-0.03	0.22	0.74	0.78	0.15	0.25	1.05
HKD - NZD	-0.01	-0.01	0.02	-0.21	0.02	0.96	0.98	0.06	0.48	1.01
CAD - CNY	0.02	0.01	0.10	-0.27	0.58					
CHF - CNY	-0.02	-0.01	0.08	-0.42	0.21					
GBP - CNY	0.06	0.05	0.12	-0.41	0.85					
AUD - CNY	0.08	0.07	0.09	-0.19	0.48					
EUR - CNY	-0.01	-0.01	0.08	-0.52	0.18					
JPY - CNY	-0.06	-0.04	0.13	-0.89	0.25					
NZD - CNY	0.15	0.13	0.15	-0.16	1.39					
HKD - CNY	0.02	0.02	0.02	-0.04	0.15	0.94	0.96	0.08	0.40	1.01
CAD - HKD	-0.86	-0.70	0.55	-2.60	0.06					
CHF - HKD	-0.21	-0.14	0.43	-2.73	0.73					
GBP - HKD	-0.91	-0.69	0.77	-6.24	1.06					
AUD - HKD	-0.74	-0.56	0.59	-3.72	0.30					
EUR - HKD	-0.77	-0.57	0.67	-4.00	0.26					
JPY - HKD	-0.91	-0.59	1.05	-5.45	0.57					
NZD - HKD	-0.31	-0.23	0.50	-2.10	1.43					
CNY - HKD	0.29	0.27	0.38	-1.30	1.34					

	Covid-19										
		Н	edge ratios			Portfolio weights					
Currencies	Mean	Median	sd	Min	Max	Mean	Median	sd	Min	Max	
CHF - CAD	0.41	0.39	0.15	0.13	1.26	0.47	0.47	0.19	-0.02	0.89	
GBP - CAD	0.65	0.63	0.24	0.18	2.32	0.24	0.22	0.17	-0.09	0.85	
AUD - CAD	1.04	1.05	0.23	0.37	2.30	0.01	-0.03	0.16	-0.20	0.79	
EUR - CAD	0.51	0.50	0.15	0.18	1.12	0.39	0.38	0.20	-0.03	0.86	
JPY - CAD	0.51	0.48	0.23	0.13	1.54	0.25	0.23	0.18	-0.03	0.77	
NZD - CAD	0.93	0.93	0.24	0.35	2.58	0.09	0.04	0.17	-0.14	0.93	
CNY - CAD	0.11	0.11	0.06	0.00	0.30	0.66	0.7	0.19	0.15	0.99	
HKD - CAD	0.01	0.01	0.01	-0.06	0.07	0.98	0.99	0.04	0.78	1.01	
CAD - CHF	0.37	0.36	0.10	0.08	0.72						
GBP - CHF	0.68	0.66	0.18	0.33	1.25	0.26	0.23	0.19	-0.07	0.98	
AUD - CHF	0.83	0.79	0.27	0.17	1.97	0.16	0.12	0.18	-0.12	1.04	
EUR - CHF	0.73	0.71	0.18	0.26	1.30	0.39	0.40	0.27	-0.15	1.14	
JPY - CHF	0.92	0.88	0.25	0.46	2.17	0.12	0.09	0.17	-0.25	1.06	
NZD - CHF	0.80	0.79	0.24	0.23	1.83	0.17	0.12	0.19	-0.10	1.08	
CNY - CHF	0.16	0.15	0.07	0.02	0.46	0.71	0.73	0.16	0.09	0.98	
HKD - CHF	0.00	-0.01	0.01	-0.03	0.02	0.97	0.98	0.03	0.80	1.00	
CAD - GBP	0.32	0.31	0.09	0.12	0.61						
CHF - GBP	0.38	0.37	0.11	0.15	0.96						
AUD - GBP	0.71	0.69	0.19	0.17	1.68	0.35	0.33	0.25	-0.12	1.11	
EUR - GBP	0.51	0.49	0.13	0.19	0.95	0.72	0.75	0.24	0.03	1.14	
JPY - GBP	0.51	0.48	0.19	0.15	1.55	0.44	0.44	0.24	-0.07	0.95	
NZD - GBP	0.65	0.63	0.17	0.19	1.72	0.39	0.37	0.25	-0.06	1.11	
CNY - GBP	0.13	0.12	0.05	0.02	0.32	0.84	0.88	0.14	0.28	1.02	
HKD - GBP	-0.01	-0.01	0.01	-0.04	0.01	0.98	0.98	0.02	0.88	1.00	
CAD - AUD	0.40	0.39	0.07	0.20	0.69						
CHF - AUD	0.35	0.34	0.11	0.15	1.21						
GBP - AUD	0.55	0.52	0.19	0.15	1.95						
EUR - AUD	0.46	0.46	0.13	0.15	0.85	0.83	0.90	0.24	0.09	1.16	
JPY - AUD	0.50	0.45	0.18	0.13	1.20	0.53	0.58	0.26	-0.04	1.11	
NZD - AUD	0.84	0.85	0.11	0.55	1.12	0.56	0.54	0.39	-0.46	1.42	
CNY - AUD	0.09	0.09	0.05	-0.01	0.28	0.86	0.89	0.13	0.31	1.01	
HKD - AUD	0.00	0.00	0.01	-0.03	0.03	0.99	0.99	0.01	0.89	1.01	
CAD - EUR	0.39	0.38	0.11	0.17	0.70						
CHF - EUR	0.62	0.62	0.16	0.24	1.51						
GBP - EUR	0.77	0.75	0.22	0.37	2.02						
AUD - EUR	0.91	0.88	0.29	0.35	2.05						
JPY - EUR	0.73	0.70	0.25	0.21	1.91	0.26	0.20	0.22	-0.09	0.86	
NZD - EUR	0.82	0.81	0.26	0.37	2.06	0.21	0.15	0.24	-0.11	0.91	
CNY - EUR	0.15	0.14	0.07	0.02	0.41	0.75	0.79	0.16	0.24	1.00	
HKD - EUR	-0.01	-0.01	0.01	-0.06	0.02	0.97	0.98	0.03	0.81	1.00	
CAD - JPY	0.21	0.20	0.08	0.07	0.45						

Table A10: Hedge ratios and portfolio weights – Covid-19 period

CHF - JPY	0.42	0.43	0.11	0.12	1.06					
GBP - JPY	0.42	0.41	0.16	0.13	0.82					
AUD - JPY	0.54	0.54	0.22	0.12	1.46					
EUR - JPY	0.40	0.39	0.13	0.11	0.78					
NZD - JPY	0.53	0.53	0.20	0.17	1.37	0.48	0.44	0.26	-0.13	1.06
CNY - JPY	0.12	0.12	0.06	0.01	0.28	0.87	0.89	0.10	0.43	1.01
HKD - JPY	0.00	0.00	0.01	-0.02	0.04	0.99	0.99	0.01	0.96	1.01
CAD - NZD	0.37	0.36	0.09	0.16	0.88					
CHF - NZD	0.36	0.34	0.14	0.12	1.35					
GBP - NZD	0.53	0.50	0.18	0.11	1.69					
AUD - NZD	0.88	0.87	0.12	0.57	1.31					
EUR - NZD	0.44	0.44	0.13	0.11	0.88					
JPY - NZD	0.51	0.48	0.17	0.19	1.29					
CNY - NZD	0.09	0.08	0.05	-0.05	0.22	0.84	0.89	0.13	0.32	1.00
HKD - NZD	0.00	0.00	0.01	-0.03	0.04	0.99	0.99	0.01	0.90	1.01
CAD - CNY	0.22	0.21	0.12	0.01	0.87					
CHF - CNY	0.33	0.32	0.13	0.07	0.86					
GBP - CNY	0.52	0.49	0.26	0.04	2.73					
AUD - CNY	0.45	0.43	0.23	-0.02	1.83					
EUR - CNY	0.38	0.35	0.17	0.05	0.99					
JPY - CNY	0.51	0.52	0.18	0.01	1.07					
NZD - CNY	0.41	0.41	0.21	-0.07	1.42					
HKD - CNY	0.00	0.00	0.02	-0.04	0.06	0.95	0.97	0.04	0.76	1.00
CAD - HKD	0.37	0.36	0.71	-2.56	2.84					
CHF - HKD	-0.50	-0.37	1.09	-8.09	1.24					
GBP - HKD	-1.45	-1.08	1.88	-12.7	1.28					
AUD - HKD	-0.25	-0.34	1.29	-6.56	2.97					
EUR - HKD	-0.59	-0.35	1.12	-5.56	2.06					
JPY - HKD	0.08	0.12	1.39	-6.10	2.92					
NZD - HKD	-0.51	-0.51	1.28	-6.53	2.21					
CNY - HKD	-0.21	-0.04	0.80	-4.12	1.35					

Note: The Tables A6-A10 display key statistical measures for the optimal portfolio weights and hedging ratios, including median, standard deviation (sd), minimum (min), and maximum (max) values. These metrics are presented for distinct time periods, as detailed in the Data section. Sub-periods are identified in Figure 2. Additionally, the dataset in question shows no evidence of the Autoregressive Conditional Heteroskedasticity (ARCH) effect, precluding the possibility of executing Asymmetric Dynamic Conditional Correlation (ADCC) analysis. The dataset encompasses the period from September 27, 2009, to April 30, 2023, and we calculate the daily variances using data at one-minute intervals. The subperiods are chosen based on the events identified as the permanently affecting connectedness in Figure 2. The date for the Greece bailout is May 2, 2010, which we endogenously identify as an end to the EU debt crisis; the US debt ceiling occurred on August 2, 2011; the Brexit referendum took place on June 23, 2016, and the date for Covid-19 outbreak was endogenously selected February 23, 2020. The portfolio weights and hedging ratios are calculated based on specification (6): $w_{j,k,t} = \frac{h_{kk,t}-h_{j,k,t}}{2}$

 $\overline{h_{jj,t}-2h_{jk,t}}+h_{kk,t}$

	USD/AUD	USD/CAD	USD/EUR	USD/GBP	USD/CHF	USD/JPY	USD/NZD	USD/CNY	USD/HKD	FROM Others
USD/AUD	21,6	11,97	11,13	10,16	9,83	9,74	14,3	5,95	6,13	78,94
USD/CAD	12,92	22,86	10,51	10,3	9,85	9,32	11,81	6,19	6,50	77,14
USD/EUR	11,37	10,14	21,54	11,00	14,27	9,78	10,65	5,67	5,58	78,46
USD/GBP	11,6	10,40	11,71	23,53	10,55	9,78	10,61	6,23	6,11	76,47
USD/CHF	10,39	9,59	14,77	10,5	22,26	10,70	10,19	6,17	5,88	77,74
USD/JPY	10,78	9,71	10,76	9,85	11,30	24,73	10,71	6,29	5,86	75,27
USD/NZD	14,19	11,26	10,70	9,76	9,75	9,60	22,63	6,07	6,04	77,37
USD/CNY	8,87	8,65	8,49	8,36	8,67	8,18	8,81	31,23	8,73	68,77
USD/HKD	8,63	8,79	7,90	7,90	8,05	7,54	8,48	9,01	33,70	66,30
TO Others	88,22	80,51	85,98	77,10	82,29	74,66	85,29	51,59	50,83	
NET Spill OVFR										
STILLOVER	9,28	3,37	7,51	0,63	4,55	-0,62	7,92	-17,18	-15,47	

Table A11: Volatility spillover table (τ =0.05)

Note: The values in the table represent the percentage of volatility shared between currencies at the 0.05 quantile. Column "FROM" demonstrates volatility received from other currencies; row "TO" demonstrates volatility transmitted to other currencies. In the row "NET SPILLOVER", we compare received and transmitted volatility. The dataset encompasses the period from September 27, 2009, to April 30, 2023, and we calculate the daily variances using data at one-minute intervals. The static volatility spillover table is calculated based on modifications of specification (2): $S_{i \leftarrow j}^{H,0,05} = \frac{Q_{0,05}(\theta_{i,j}^g(H))}{\sum_{j=1}^N Q_{0,05}(\theta_{i,j}^g(H))}$ for spillovers FROM variable(s); $S_{i \to j}^{H,0,05} = \frac{Q_{0,05}(\theta_{i,j}^g(H))}{\sum_{j=1}^N Q_{0,05}(\theta_{i,j}^g(H))}$ for spillovers.

	USD/AUD	USD/CAD	USD/EUR	USD/GBP	USD/CHF	USD/JPY	USD/NZD	USD/CNY	USD/HKD	FROM Others
USD/AUD	14,60	11,4	10,96	10,29	11,00	10,55	11,36	9,72	10,48	85,40
USD/CAD	11,24	14,96	10,83	10,56	10,76	10,45	10,89	9,62	10,68	85,04
USD/EUR	10,73	10,89	14,78	10,36	12,11	10,48	10,82	9,30	10,53	85,22
USD/GBP	10,49	10,80	10,96	14,88	11,8	10,38	10,63	9,83	10,96	85,12
USD/CHF	10,44	10,32	11,73	10,23	15,59	10,90	10,27	9,45	11,7	84,41
USD/JPY	10,58	10,39	10,72	10,17	11,27	15,20	10,62	10,5	10,98	84,80
USD/NZD	11,57	10,70	10,65	10,30	10,87	10,38	15,60	9,37	10,56	84,40
USD/CNY	10,31	9,87	10,27	10,36	10,76	10,39	10,15	16,56	11,33	83,44
USD/HKD	10,19	10,22	9,86	10,2	10,49	10,43	10,90	10,49	17,40	82,60
TO Others	85,56	84,24	85,99	82,30	88,33	83,94	85,65	77,83	86,59	
NET										
SFILLOVER	0,15	-0,80	0,77	-2,82	3,92	-0,85	1,25	-5,62	4,00	

Table A12: Volatility spillover table (τ=0.95)

Note: The values in the table represent the percentage of volatility shared between currencies at the 0.95 quantile. Column "FROM" demonstrates volatility received from other currencies; row "TO" demonstrates volatility transmitted to other currencies. In the row "NET SPILLOVER", we compare received and transmitted volatility. The dataset encompasses the period from September 27, 2009, to April 30, 2023, and we calculate the daily variances using data at one-minute intervals. The static volatility spillover table is calculated based on modifications of specification (2): $S_{i\leftarrow j}^{H,0,95} = \frac{Q_{0,95}(\theta_{i,j}^g(H))}{\sum_{j=1}^N Q_{0,95}(\theta_{i,j}^g(H))}$ for spillovers FROM variable(s); $S_{i\to j}^{H,0,95} = \frac{Q_{0,95}(\theta_{i,j}^g(H))}{\sum_{j=1}^N Q_{0,95}(\theta_{i,j}^g(H))}$ for spillovers FROM variable(s); $S_{i\to j}^{H,0,95} = \frac{S_{i\to j}^{H,0,95}}{S_{i\to j}^{I}} - S_{i\leftarrow j}^{H,0,95}$ for net spillovers.

	Connectedness	US_TED rate	US CDS	US 5-year yield	USD-EUR bid-	US_EPU	ld_SP500
					ask spread		
Connectedness	1,00	0,13	0,25	-0,58	0,12	0,36	0,00
US_TED rate		1,00	0,27	0,08	0,20	0,10	-0,03
US CDS			1,00	-0,28	0,19	-0,04	-0,02
US 5-year yield				1,00	-0,09	-0,45	-0,03
USD-EUR bid-ask					1,00	-0,02	-0,06
spread							
US_EPU						1,00	0,02
ld_SP500							1,00
US 5-year yield USD-EUR bid-ask spread US_EPU Id_SP500				1,00	-0,09 1,00	-0,45 -0,02 1,00	-0,03 -0,06 0,02 1,00

Table A13: Correlation matrix

Note: S&P500 index was transformed by logarithmic difference; US CDS represents US 5-year credit default swap rate; US_EPU represents US daily Economic policy uncertainty index.