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Connectedness of money market instruments: A time-varying vector autoregression approach

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Abstract

The heightened volatility of LIBOR rates relative to other money market funding rates following the 2012 manipulation scandal and the 2007/2008 global financial crisis led to financial regulators' recommendation to transit to more robust rates. During this period, uncertainty and heightened credit risks led to the drying up of liquidity in underlying money markets, especially for the longer-dated money market instruments. The need to shift to alternative rates was reinforced during the covid-19 crisis in March 2020 when the LIBOR rates' vulnerability to short-term liquidity, and therefore volatility was amplified. This paradigm shift has economic and financial consequences. While connectedness studies exist for various financial markets and/or instruments, studies on money markets are limited. This is despite the uniqueness of money markets. This study fills the gap by investigating the volatility connectedness of overnight index swaps, LIBOR rates, and foreign exchange swaps using the time-varying vector autoregressive model. Specifically, the study measures the extent and dynamic connectedness of three major currencies (EUR, GBP, and JPY) in three maturity categories (1-month, 3-month and 6-month), for the period 2007-2020. The findings show that the connectedness of instruments is time-varying, event dependent for these currencies, with a high integration during crisis periods. However, the integration reduces when markets are calm. Notably, the bi-directional volatility connectedness of instruments varies across currencies. This is not surprising considering the domestic institutional and monetary policy specificities affecting these currencies.

Keywords: LIBOR; foreign exchange swaps; overnight index swaps; volatility connectedness; monetary transmission mechanism.

JEL codes: E43; E52; G15; F3; C5.

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1. Introduction

The heightened volatility of the London Interbank Offered Rate (LIBOR) rates relative to other money market[2] funding rates following the 2012 manipulation scandal and the 2007/2008 global financial crisis (GFC) led to financial regulators' recommendation to transit to more robust rates (Bank for International Settlements [BIS], 2013). During this period, uncertainty and heightened credit risks led to the drying up of liquidity in underlying money markets, especially for the longer-dated money market instruments (Houe and Skie, 2014). The need to shift to alternative rates was reinforced during the covid-19 crisis in March 2020 when the LIBOR rates' vulnerability to short-term liquidity, and therefore volatility was amplified (Bank of England, 2020).

Efforts to transit away from LIBOR to alternative money market rates are underway in various jurisdictions. For instance, the United States, United Kingdom, and Japan have selected the Secured Overnight Financing Rate (SOFR), Sterling Overnight Index Average (SONIA), and Tokyo Overnight Index Average (TONAR), respectively, as alternative reference rates (Schrimf and Sushko, 2019). Notable is that jurisdictions are faced with different alternative reference rates. To achieve "robustness", arguably, one of the crucial considerations of a reference rate is that it should track the movements of the central bank target rate. This is because central banks achieve the monetary and price stability objectives through their influence on short-term money market instruments and market expectations. To this effect, understanding the behaviour of available alternative rates and their correlation with others is therefore critical.

Unexpected behaviour of reference rates and their correlation with others can lead to unintended consequences on the economy. While this is critical, problematically, empirical studies on the behaviour and co-movements of potential reference rates remain limited. This is because reference rates have only received considerable attention following the 2007-08 GFC and covid-19 crises. This paper fills this gap by empirically investigating the volatility connectedness across money market instruments and maturity categories for three major currencies. To the best of my knowledge, this is the first study to investigate the extent and dynamic connectedness of overnight index swaps (OIS), LIBOR rates and foreign exchange swaps for 1 month (M), 3M and 6M maturity categories for the Euro (EUR), Pound Sterling (GBP) and Japanese Yen (JPY).

The importance of the findings is twofold. First, reference rates have implications for the effectiveness of the monetary transmission mechanism (MTM). This is because short-term

[2] Frederic S. Mishkin (2019) defines the money market as a market in which short-term debt instruments with an original maturity of less than one year are traded.

interest rates are the first step of the interest rate channel of the MTM. Specifically, the behaviour of short-term interest rates in times of stress and calm periods has implications for the effectiveness of MTM. For example, the unexpected behaviour of short-term interest rates during stress may present challenges in transmitting monetary policy to the real economy. Second, the findings inform the choice of alternative benchmarks (reference rates) for various jurisdictions.

2. Background and Literature Review

The drying up of liquidity (structural changes) in underlying markets and compromised integrity of LIBOR and equivalent rates following the series of manipulation scandals, led to financial market regulators' recommendation to shift to alternative near risk-free rates. This paradigm shift entails moving from the once "most widely referenced" benchmark in the world (LIBOR) to alternative near risk-free rates. The near risk-free rates should meet the criteria of a good benchmark which include representativeness, robustness, reliability, and transparency (IOSCO, 2013). This study focuses on "robustness". Robustness means that a benchmark or reference rate should be available and usable in stressed market conditions (BIS, 2013).

Notable during the 2007-08 GFC was the unexpected behaviour of the LIBOR relative to other short-term funding rates. Before the crisis, LIBOR moved in tandem with other short-term funding rates. There was an increase in the level and volatility of LIBOR spreads on short-term funding rates including central bank target rates, treasury bills, and OIS. This raised questions regarding the robustness of LIBOR, and its usability in crisis periods. This behaviour was repeated during the Covid-19 crisis in March 2020. As the Bank of England (2020) reported:

"Recent market volatility has highlighted the long-standing weaknesses of LIBOR benchmarks, which remain in widespread use. LIBOR rates - and hence costs for borrowers - rose as central bank policy rates fell, and underlying market activity was low. This has reinforced the importance of completing the transition to alternative rates by end-2021."

From a central bank perspective, a robust reference rate or financial benchmark is one that effectively transmits monetary policy from the target rate to the real economy. This is because reference rates affect the financing conditions of the economy and therefore the real economy (Kawata et al., 2012). The effect of the reference rates on the real economy is dependent on the link between the central bank target rate (official rate) and the reference rate (BIS, 2013). Unexpected volatility or behaviour of the reference rate may lead to unintended consequences on the real economy (Sudo, 2012). Countries use different monetary policy target rates to achieve their inflation objectives. Most central banks target the short end of the yield curve. The central bank target rates and reference rates range from unsecured interbank rates to secured rates (e.g., repo rates, implied foreign exchange swap rates).

Alternative risk-free rates are preferred to LIBOR or IBOR equivalent rates because, among other attributes, their movements are perceived to be in tandem with central bank official rates and can be relied upon for effective MTM. These rates range from unsecured rates to secured rates. For example, the Bank of England has selected an unsecured overnight index, Sterling Overnight Index (SONIA) as an alternative risk-free interest rate. The SONIA, a measure of unsecured wholesale deposits is the preferred alternative as its movements are more stable than other rates and tracks the movements of the Bank of England target rate (Bank of England, 2017).

While general information on preferred and potential alternative risk-free rates is available, empirical studies on their behaviour and co-movements with other short-term funding rates (volatility spillovers) remain limited. Most available studies on reference rates focus on manipulation (Molenkamp, 2008; Molenkamp and Whitehouse, 2008; Kuo et al., 2018; Gyntelberg and Wooldridge, 2008; Abrantes-Metz, Villas-Boas and Judge, 2011; Abrantes-Metz et al., 2012; Monticini and Thornton, 2013). This study addresses this gap by assessing the behaviour and co-movements of the LIBOR and equivalent IBORs, and selected alternative near risk-free rates (potential benchmarks).

3. Data and Methodology

3.1. Data

This study uses daily data for three instruments, namely OIS, LIBOR and Euro Interbank Offered Rate (EURIBOR) rates and foreign exchange swap implied rates (FXIRs) for 1M, 3M and 6M maturity categories. Daily comprehensive data for the period 2/1/2007 to 31/12/2020 collected from Bloomberg is used. This study period is purposively selected as it captures the pre and post-crisis periods. The 1M, 3M, and 6M maturity categories are purposefully selected to capture the very short-end, medium-term, and long-term part of the money market yield curve for different instruments, respectively.

As Stenfors (2013) states, short-term money market rates are highly determined by central bank actions regardless of the type of instrument[3]. Consequently, the very short-term part of the money market yield curve for the OIS, LIBOR and FXIRs captures central bank announcements, that is, the transmission of monetary policy from the central bank policy rates to the short end of the money market yield curve. To capture this aspect, the 1M maturity category is used. It is preferred to the official and available ultra-short-term[4] money market rates (e.g., overnight, spot-next, 7 days) as it is less volatile.

The 3M maturity category captures the medium part of the money market yield curve. Specifically, for the LIBOR, it is the most referenced tenor. It, therefore, allows for capturing the propagation of shocks from the very - short-end to the medium-term and long-term part of the money market yield curve. The 6M maturity category captures the longest tenor of the money market yield curve (9M &12M) as for the LIBOR the 9M maturity category was discontinued in 2013 while it is more liquid than the 12M maturity category.

As regards the selection of money market instruments, foreign exchange swaps, OIS, and LIBOR rates warrant analysis. First, these instruments are widely used and highly liquid in global financial markets. Second, they represent different money market segments thereby offering insights into these segments. In terms of their use, liquidity metrics such as turnover indicate that the foreign exchange swap is the most traded instrument and accounts for 49 percent of the global foreign exchange trading in 2019. This is an increase from 47 percent in 2016 (BIS, 2019a). While this is the case, foreign exchange swaps have received limited attention from academics and regulators (Stenfors, 2018). The OIS market as revealed by the BIS (2019b) accounts for almost 50 percent of the average daily turnover (US$ 2 trillion) of all interest rate swaps (US$ 4.1 trillion). On the other hand, by mid-2018, the LIBOR stood as the most widely referenced interbank rate underpinning financial contracts worth US$ 400 trillion by mid-2018 (Schrimpf and Shusko, 2019).

To understand the different money market segments these instruments are from, definitions and examples follow below. Specifically, an OIS is an over-the-counter interest rate derivative where two participants agree to exchange fixed and floating interest payments on a notional principal for an agreed period. It involves the exchange of a fixed rate for a period (e.g., 1M, 3M, 6M) for the geometric average of the overnight rates during the period (Hull, 2015). The geometric average considers the fact that the notional principal

[3] Given the monopoly power of central banks as issuers of currency, they have the power to influence/determine short-term money market rates. The starting point is the change in central bank official rates which should immediately be transmitted to other short-term market rates (European Central Bank, 2021; Bank of England, 2022b).

[4] Muchimba and Stenfors categorise the overnight to 7 days as the ultra-short-term of the money market.

and accrued interest are reinvested for the duration of the contract. The OIS is calculated as follows (ISDA, 2021):

$$OIS = [\prod_{i=1}^{d_o}\left(1 + \frac{Benchmark\ Level_{i*}n_j}{Day\ Count\ Basis}\right) - 1] * \frac{Day\ Count\ Basis}{d} \quad (1)$$

Where d_o is the number of applicable business days until maturity in a calculation period, i is the applicable business day in a series of whole numbers from 1 to d_o, each representing the relevant applicable business day in chronological order from, and including, the first applicable business day in the calculation period. $Benchmark\ Level_{i*}n_j$ represents floating rate for the applicable business day[5]. $Day\ Count\ Basis$ is the assumption for the number of days in a year.

The fixed rate in an OIS contract is referred to as the OIS rate. If the geometric average of daily rates is less than the fixed rate, then the fixed rate payer pays the floating rate payer at the end of the period. For a vanilla OIS for a year or less, there is no exchange of cashflow, and funds are only exchanged at the conclusion of the contract. To this effect, the OIS contract has limited liquidity and counterparty risk and is regarded as a risk-free asset reflecting both current and expected future overnight interest rates over the horizon of the contract. To this effect, OIS, as risk free rates are used to represent market expectations of future short-term central bank interest rates, which according to the MTM logic, should transmit shocks to other instruments. It is therefore a good candidate to represent market expectations in the analysis.

To capture the transmission of volatility in the unsecured money market segments for the GBP, JPY and Euro currencies the respective IBOR rates are used. Specifically, GBP LIBOR, JPY LIBOR and EURIBOR rates are used for the analysis[6]. LIBOR and EURIBOR rates are good

[5] The OIS varies across jurisdictions due to different market conventions for each currency. The floating reference rates (central bank rates) used in the OIS calculation are the Federal Funds rate, SONIA, EONIA, and TONAR for the United States, United Kingdom, Euro area, and Japan, respectively.

[6] There have been several different LIBOR currencies over the years. Over time, some financial centers developed their own LIBOR-equivalent benchmarks. For instance, Swedish Krona (SEK) LIBOR – Stockholm interbank Offered Rate (STIBOR), Danish Krone (DKK) LIBOR – Copenhagen Interbank Offered Rate (CIBOR), Australian Dollar (AUD) LIBOR – Bank Bill Swap (BBSW), Canadian Dollar (CAD LIBOR) – Canadian Dollar Offered Rate (CDOR), EUR LIBOR – EURIBOR, JPY LIBOR – Tokyo Interbank Offered Rate (TIBOR). The GBP, USD, Swiss Franc (CHF) LIBORs do not have alternatives. The JPY LIBOR and JPY TBOR are almost equally important and used. In terms of liquidity, all other LIBORs (including SEK, DKK, and EUR) are rarely used in any derivatives (or less than 0.1 and policy making.

candidates as they capture the existing realities in interbank markets such as liquidity, credit and term risk premia.

Since LIBOR rates are derived from the unsecured market segment and there is an exchange of cashflow between parties, they should reflect liquidity, credit, and term premia over and above the OIS. Mathematically, in a market where OIS is tradeable, the LIBOR or equivalent IBOR rate for a given currency and maturity category can be expressed as follows (Bank of England, 2007):

$$LIBOR_t = OIS_t + Risk\ Premia_t \quad (2)$$

Where OIS_t represents the OIS rate (in an observable market) on day t for a specific currency and maturity. $LIBOR_t$ is the LIBOR rate (equivalent IBOR) fixing on day t for the respective currency and maturity category. Decomposing the risk premia (Poskitt, 2011; Stenfors, 2013):

$$Risk\ Premia_t = CRED_t + FUNDLIQ_t + MKTLIQ_t \quad (3)$$

Where $CRED_t$ is the premium related to credit risks of the LIBOR contributors at time t, $FUNDLIQ_t$ is the premium associated funding liquidity risks of the LIBOR contributors at time t. $MKTLIQ_t$ is the premium related to the overall liquidity in the market. Theoretically, an illiquid market contributes to a higher risk premium, and therefore higher LIBOR rate at time, keeping other variables constant. In a market without dislocations, liquidity and credit risks, LIBOR or equivalent IBOR can be expressed as:

$$LIBOR_t = OIS_t \quad (4)$$

As postulated by the Expectations Hypothesis, the OIS should be as close as possible to the LIBOR of equivalent maturity (European Central Bank, 2011). For example, the 3M GBP LIBOR should be as close as possible to the 3M OIS. Any difference will reflect the liquidity and credit premia. For monetary policy to be effective, market expectations (OIS) should be transmitted to interbank money market rates, such as, the LIBOR, and EURIBOR.

A Foreign exchange swap represents a collateralised segment of the money market. It is a bilateral contract where parties agree to exchange two different currencies with an agreement to unwind this transaction in future. To derive the implied rates, the Covered Interest Rate Parity (CIP) formula is used. According to Borio et al. (2016) the CIP is also known as the "physical law in international finance." Given two currencies, the USD and the Japanese Yen, mathematically, the CIP formula is expressed as:

$$\frac{F}{S} = \frac{(1+r)}{1+r^{*}} \qquad (5)$$

Where F and S represent the respective forward and spot exchange rate between the USD and the JPY. r represents the JPY interest rate while r^{*}represents USD interest rate. In reality, banks do not quote forward rates to each other but instead quote foreign exchange swap price. mathematically, the forward outright is expressed as:

$$FX\ forward = FX\ Spot + FX\ Swap \qquad (6)$$

Rewriting equation (5) in relation to equation (6), the $(FX\ Swap)$ can be rewritten as:

$$FX\ Swap = S[\left(\frac{1+r}{1+r^{*}}\right) - 1] \qquad (7)$$

Given the $FX\ Swap$ (expressed in pips), the USD/JPY spot rate, the USD money market interest rate (USD LIBOR), the JPY FXIR can be derived as follows:

$$FXIR = \left[\left(\frac{F+S}{S}\right) * (1 + r^{*})\right] - 1 \qquad (8)$$

Annualising the interest rates, the FXIR for a currency is calculated as follows:

$$FXIR = \left[\left\{\left(\frac{F+S}{S}\right) * \left(1 + (r^{*} * \frac{d}{DCB(Base\ Currency)}\right) - 1\right\}\right] * \left[\frac{DCB(Counter\ Currency)}{d}\right] \qquad (9)$$

Where the d is the number of business days in the respective calculation period. $DCB(Base\ Currency)$ is the assumption for the number of days in a year for the base currency. This equation shows that the FXIR for a currency is related to developments in the funding currency (the USD in this case). For this study, the implied rates are derived using the foreign exchange forward points (mid rates) and the USD LIBOR as the funding currency to raise the EUR, GBP and JPY in the respective EUR/USD, GBP/USD, and USD/JPY foreign exchange swaps.

To understand the relationship between the foreign exchange swap and LIBOR and Equivalent IBOR, important to note is the fact that a bank when in need of the domestic currency can source it from the secured or unsecured interbank market segment. In the foreign exchange swap market segment, a bank can use a foreign currency to engage in a foreign exchange swap transaction. They have minimum credit risk as the borrowing is covered by collateral. Using the USD and Japanese Yen example. A domestic financial institution in need of the Japanese Yen in Japan can use a foreign currency (USD) to exchange the later for the former, with an agreement to unwind the transaction in future. The total funding cost of the Japanese Yen in this market is called the JPY FXIR rate. In a frictionless market where participants can exploit arbitrage opportunities, the following CIP condition should hold:

$$(1 + r^*) = \frac{F}{S}(1 + r) \tag{10}$$

Where $1 + r^*$ represents the money market cash rate (e.g., JPY LIBOR rate) while $\frac{F}{S}(1 + r)$ is the foreign exchange swap implied rates (e.g., implied JPY rate). Otherwise, if there are deviations, the CIP fails to hold. In this case:

$$(1 + r^*) + P = \frac{F}{S}(1 + r) \tag{11}$$

P is the CIP deviation which shows the premium paid to the JPY lender in the unsecured interbank market. The higher P is normally associated with the credit worthiness of the banks in the market. To this effect, there is a relationship between the foreign exchange swap market (implied rates) and unsecured interbank markets (LIBOR rates). For example, developments in the foreign exchange swap market can spillover to the unsecured interbank market, and vice versa.

3.2. Methodology

To measure and assess co-movements of economic variables overtime (dynamic transmission of shocks) in a network, Diebold and Yilmaz (2009, 2012,2014) is a widely applied framework (e.g., Cronin, 2014; Grobys, 2015; Antonakakis and Kizys, 2015). The Diebold and Yilmaz model provides both the static and dynamic analysis of the network using the Vector Autoregressive Model (VAR) developed by Sims (1980). This framework has been refined resulting into variant connectedness approaches, that is, quantile connectedness approach (Chatziantoniou, Gabauer and Stenfors, 2020), asymmetric connectedness approach (Baruník, Kocˇenda and Vácha, 2017), DECO-GARCH model and the spillover index (Kang, Mclver and Yoon, 2017), wavelet connectedness approach (Antonakakis et al., 2018),frequency connectedness approach (Baruník and Kˇrehlík, 2018), Elastic-Net and Ridge Connectedness Approach (Gabauer et al. , 2020).

While the variants are useful, most of them rely on static analysis of the VAR model, and the dynamic analysis uses the rolling-window VAR method. This method has three inherent weaknesses. First, it does not address the fact that the dynamics can be affected by the size of the rolling window. Second, outliers may alter outcomes. Third, observations may be excluded when moving across windows (Chatziantoniou, Gabauer and Stenfors, 2020). To address these weaknesses, Antonakakis (2019) developed the Time Varying Vector Autoregressive (TVP-VAR) Model. To this effect, this study uses the TVP-VAR model to measure the extent and dynamic connectedness of selected short-term reference rates. This approach focusses on variance decompositions, which are widely understood and calculated. The variance decompositions allow for the aggregation of spillover effects across instruments extracting a wealth of information into a single spillover measure. For each currency, the following TVP-VAR model is estimated as suggested by the Bayesian Information Criteria (BIC) is estimated for the three instruments and maturity categories:

$$Z_t = B_t Z_{t-1} + u_t \qquad u_t \sim N(0, S_t) \tag{12}$$

$$vec(B_t) = vec(B_{t-1}) + v_t \quad v_t \sim N(0, R_t) \tag{13}$$

Where Z_t, Z_{t-1} and u_t are kX1 dimensional vectors, representing all variables (FXIRs, LIBOR rates (GBP and JPY), and EURIBOR, and OIS for the 1M, 3M and 6M maturity categories) in t, t-1, and the respective error term. B_t and S_t are kXk dimensional matrices, $vec(B_t)$ and v_t are k^2X1 dimensional vectors and R_t is a K^2xK^2 dimensional matrix.

The H-step ahead (scaled) generalized forecast error variance decomposition (GFEVD) by Koop et al. (1996) and Pesaran and Shin (1998) are calculated. Importantly, the GFEVD is completely invariant to the variable ordering, contrary to the orthogonalized forecast error variance decomposition (Diebold and Yilmaz, 2009).

In macroeconomics as with practice, an underlying theory should guide structural representations for the respective shocks (Chatziantoniou, Gabauer and Stenfors, 2020). To the best of my knowledge, such a theory for money market instruments (FXIRs, OIS and LIBOR rates) does not exist. In this regard, the GFEVD is utilised in line with Wiesen et al. (2018) who postulate that this analysis should be employed when theory does not exist. As this representation is based on Wold representation theorem, the estimated TVP-VAR model is transformed into a TVP-VMA process:

$$z_t = \sum_{i=1}^{p} B_{it} z_{t-i} + u_t = \sum_{j=0}^{\infty} A_{jt} u_{t-j} \qquad (14)$$

The (scaled) GFEVD normalises the unscaled GFEVD, $\emptyset_{ij,t}^{g}(H)$ so that each row sums to 1. In this regard, $\widetilde{\emptyset_{ij,t}^{g}}(H)$ represents the influence on variable i's forecast error variance of from variable j, also called pairwise directional connectedness from j to i.

$$\emptyset_{ij,t}^{g}(H) = \frac{S_{ii,j}^{-1} \sum_{t=1}^{H-1} (i'_i A_t S_t i_j)^2}{\sum_{j-1}^{k} \sum_{t=1}^{H-1} (i_i A_t S_t A_t'^{\prime} i_i)} \qquad (15)$$

$$\widetilde{\emptyset_{ij,t}^{g}}(H) = \frac{\emptyset_{ij,t}^{g}(H)}{\sum_{j=1}^{k} \emptyset_{ij,t}^{g}(H)} \qquad (16)$$

Where $\sum_{j=1}^{k} \widetilde{\emptyset_{ij,t}^{g}}(H) = 1$, $\sum_{j=1}^{k} \widetilde{\emptyset_{ij,t}^{g}}(H) = k$ and i corresponds to a selection vector with unity on the i^{th} position and zero, otherwise.

Based on the GFEVD, the following connectedness measures are derived as per Diebold and Yilmaz (2012,2014)

$$TO_{jt} = \sum_{i=1, i \neq j}^{k} \widetilde{\emptyset}_{ij,t}^{g}(H) \qquad (17)$$

$\widetilde{\emptyset}^g_{ij,t}$ is the impact of a shock in variable j has on variable i, therefore $TO_{jt} = \sum_{i=1,i\neq j}^{k} \widetilde{\emptyset}^g_{ij,t}(H)$ represents the aggregated impact a shock on variable j has on all other variables, also referred to as total directional connectedness to others.

$$FROM_{jt} = \sum_{i=1,i\neq j}^{k} \widetilde{\emptyset}^g_{ij,t}(H) \tag{18}$$

$FROM_{jt} = \sum_{i=1,i\neq j}^{k} \widetilde{\emptyset}^g_{ij,t}(H)$ shows the aggregated influence that all the other variables have on variable j, also referred to the total directional connectedness from others.

$$NET_{jt} = TO_{jt} - FROM_{jt} \tag{19}$$

Subtracting the impact variable j has on others by the influence of others have on variable j leads to the net total directional connectedness, which provides information regarding whether a variable is a net transmitter or net recipient of shocks. If $NET_{jt} > 0$, then the variable is a net transmitter of shocks, and if $NET_{jt} < 0$, then the variable is the net recipient of shocks.

$$TCI_t = k^{-1} \sum_{j=1}^{k} TO_{jt} \equiv k^{-1} \sum_{j=1}^{k} FROM_{jt} \tag{20}$$

TCI, the total connectedness index represents the average impact one variable has on all others, if this measure is relatively high, it means that the interconnectedness of the network is high and therefore the market risk is high, as a shock in one will influence all the other variables. A low value demonstrates that most variables are independent from each other which in turn means that a shock in one variable will not cause other variables to change, resulting into low market risk.

$$NPDC_{ij,t} = \widetilde{\emptyset}_{ij,t}(H) - \widetilde{\emptyset}_{ji,t} \tag{21}$$

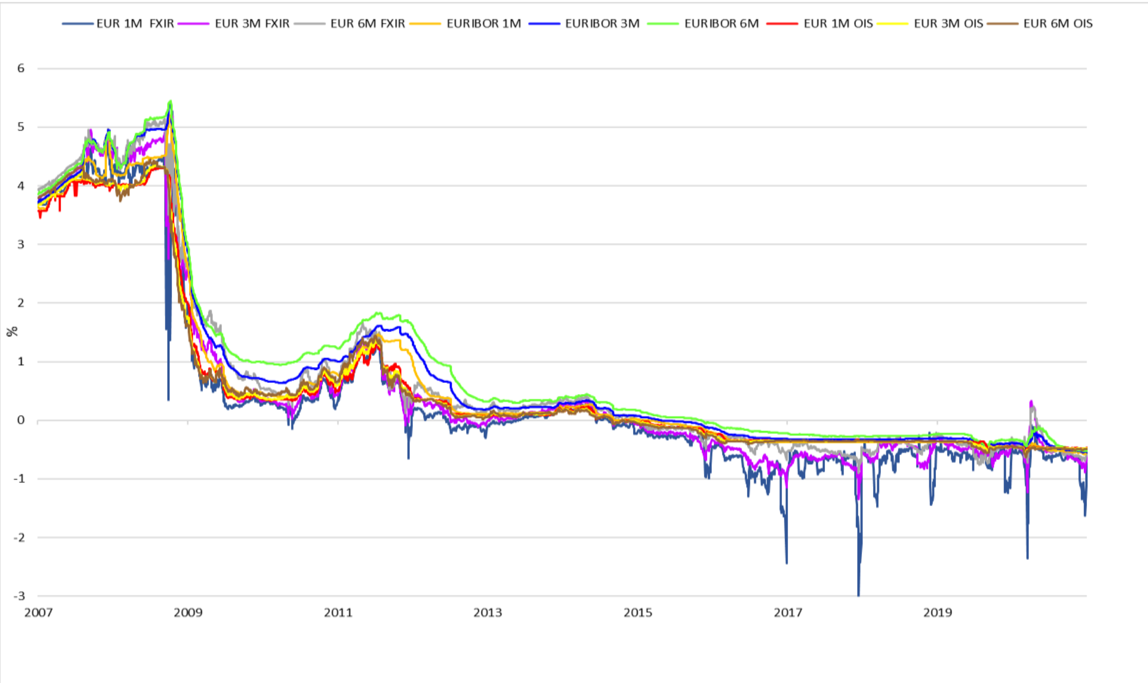
Since all variables above offer information on an aggregated basis, $NPDC_{ij,t}$ indicates the bidirectional relationship between variable j and i. The net pairwise directional connectedness demonstrates whether variable i is driving variable j, and vice-versa. In this case, the impact variable i is subtracted from variable j, or vice versa. If $NPDC_{ij,t} > 0$, then variable I is dominating, and if $NPDC_{ij,t} < 0$, then variable i is being dominated by variable j.

4. Empirical Results

4.1. EUR interest rates

Figure 1 below shows the EUR interest rates for the period, 2/1/2007 – 31/12/2020. Notable is that the interest rates remained elevated during the 2007-08 GFC. The perceived heightened credit and liquidity risks kept the money markets rate high. In response, the European Central Bank cut the rate thrice to 2.5% in December 2008. This was accompanied by liquidity provision to the banking sector including longer money market maturities. This eased the liquidity conditions and kept the money market rates low (European Central Bank, 2022).

Figure 1 EUR Interest rates 2/1/2007 – 31/12/2020



Source: Bloomberg and author's calculations

Notes: The EUR interest rates represent foreign exchange swap implied rates (EUR 1M FXIR, EUR 3M FXIR, and EUR 6M FXIR), EURIBOR rates (EURIBOR 1M, EURIBOR 3M, and EURIBOR 6M), and overnight index swaps (EUR 1M OIS, EUR 3M OIS, and EUR 6M OIS). The implied rates are calculated using the USD as the funding currency in the EUR/USD currency pair, the 1M, 3M, and 6M USD LIBOR rates are used to represent the respective USD interest rates.

Table 1 below shows the summary statistics for EUR interest rates for the period 2/1/2007-31/12/2020. The statistics show that the 6M tenor for all money market instruments has higher variability than the 1M and 3M maturity categories. The high variability of the 6M is attributable to the structural decline in liquidity in unsecured money especially tenors beyond 7 days, typically overnight (Muchimba and Stenfors, 2021). The Elliot, Rothenberg, and Stock (ERS)[7] show that the series are non-stationary (Elliot et. al., 2016). To avoid spurious regression, the series become stationary when differenced once (Figure 2). Additionally, the skewness and kurtosis series in Table 1 show that the series are not normally distributed (D'Agostino, 1970; Jarque and Bera 1980; Anscombe and Glynn, 1983). Further, Q(20) and Q2 (20) are the weighted Ljung-Box statistic tests for serial correlation in the returns and squared series show evidence of autocorrelation in the series (Fisher and Gallagher 2012). The characteristics of the data show that the TVP-VAR model is an appropriate economic analysis framework.

[7] ERS is the modified version of the Augmented Dickey-Fuller (ADF) test. It has higher power for all data generating process processes as it detrends data for an efficient ADF test.

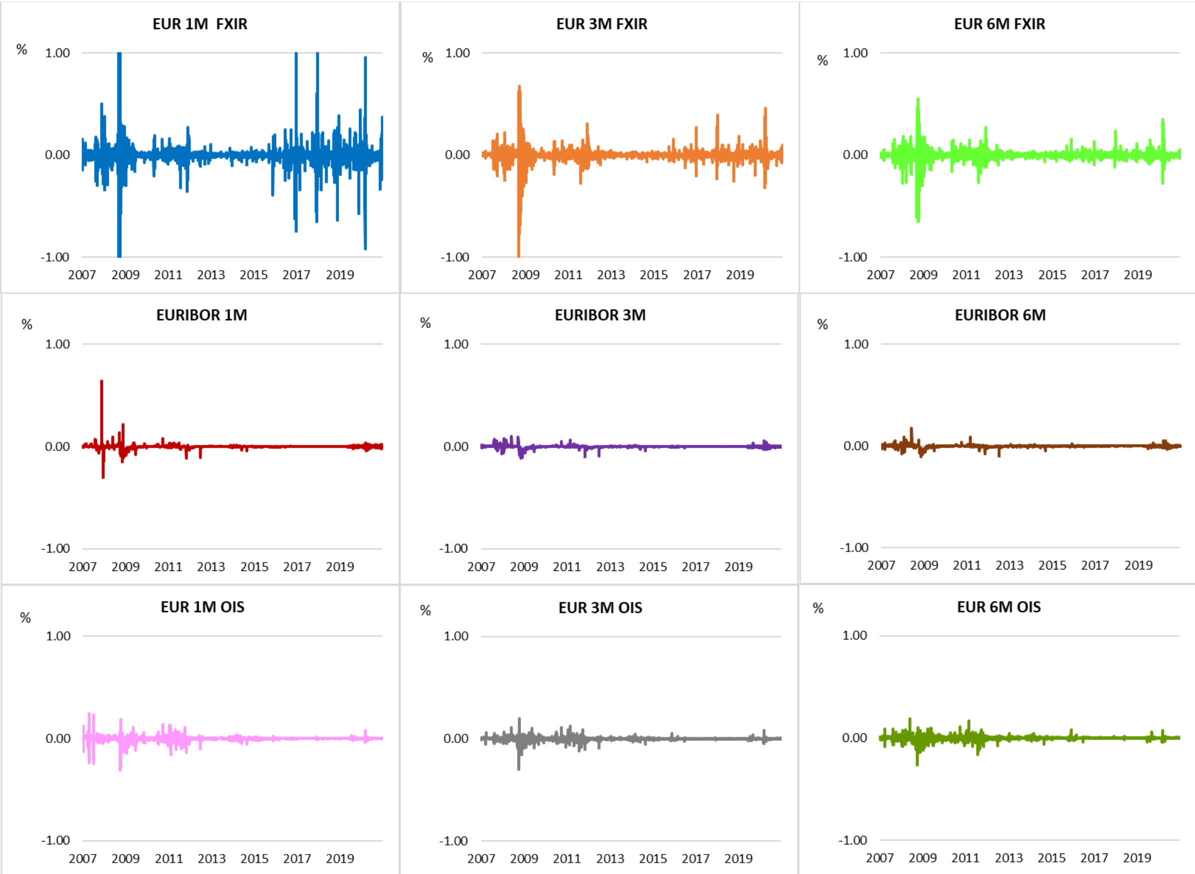
Table 1 Summary statistics: EUR Interest rates

	EUR 1M FXIR	EUR 3M FXIR	EUR 6M FXIR	EURIBOR 1M	EURIBOR 3M	EURIBOR 6M	EUR 1M OIS	EUR 3M OIS	EUR 6M OIS
Observations	3,529	3,529	3,529	3,529	3,529	3,529	3,529	3,529	3,529
Mean	0.4124	0.5687	0.7284	0.6818	0.8322	0.9581	0.5825	0.5824	0.5894
Variance	2.4872	2.6221	2.6648	2.3359	2.5891	2.6106	2.0046	2.0385	2.0810
Skewness	1.63***	1.67***	1.61***	1.64***	1.57***	1.47***	1.73***	1.75***	1.74***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Ex. Kurtosis	1.45***	1.43***	1.26***	1.30***	1.16***	0.93***	1.55***	1.60***	1.61***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
JB	1861.52***	1937.92***	1757.60***	1832.20***	1646.23***	1388.22***	2118.81***	2169.12***	2157.19***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
ERS	-0.93	-0.77	-0.73	-0.70	-0.69	-0.71	-0.65	-0.65	-0.66
	(0.3530)	(0.4440)	(0.4680)	(0.4860)	(0.4880)	(0.4810)	(0.5130)	(0.5150)	(0.5120)
Q(10)	18789.17***	19055.12***	19087.75***	19132.15***	19167.74***	19162.97***	19094.62***	19083.00***	19062.19***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Q2(10)	18669.34***	19033.40***	19102.72***	19176.98***	19247.89***	19238.58***	19158.77***	19141.57***	19103.82***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)

Source: Bloomberg and author's calculations

Notes: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$. ( ) denote standard errors. The D'Agostino (1970) and Anscombe and Glynn (1983) statistics are used for skewness and kurtosis. JB (Jarque and Bera 1980) is the test for Normality. The Elliot, Rothenberg, and Stock (ERS) unit root tests for stationarity (Elliot et al. 1996), Q(20) and Q2 (20) are the weighted Ljung-Box statistic for serial correlation in the returns and squared series (Fisher and Gallagher 2012), respectively.

Figure 2 First differenced EUR interest rates



Notes: the EUR differenced interest rate series are stationary at 1 percent level of significance.

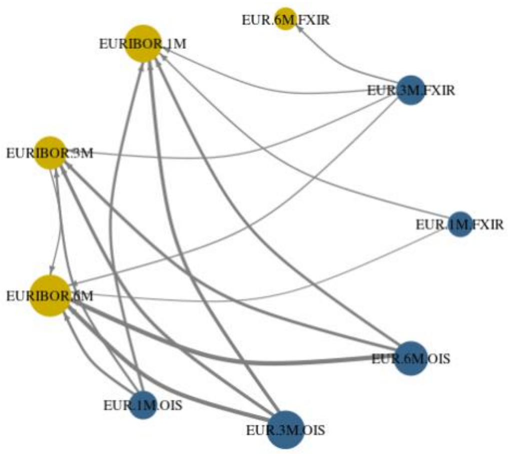
4.1.1. Static volatility connectedness - EUR interest rates

To understand the empirical results the connectedness indices presented in this section are explained in detail. Table 2 and Figure 3 below show the static connectedness of EUR interest rates (FXIRs, OIS, and EURIBOR rates). Table 2 below shows the average connectedness measures namely, TCI, on-diagonal, off-diagonal elements, “TO”, “FROM”, “NET”, and net pairwise directional connectedness (NPDC). The TCI measures the extent of the connectedness of variables in a network. It is the average impact a variable has on others in the network. A TCI of 0 means that the variables of interest are not related and are thus independent of each other. This means that variables in the system do not adjust when there is a shock in one variable. On the other hand, a value of 100, means that the variables in question are highly connected. A measure close to 100 means that a shock of one variable will cause other variables to adjust in the system. From a risk perspective, a high TCI shows high uncertainty as variables are highly interconnected (Chatziantoniou, Gabauer and Stenfors, 2021). From a monetary policy transmission perspective, the higher the TCI, the higher the chance that variables will adjust to monetary policy actions.

The TCI at 66.41 in Table 2 is an indication that the network of EUR interest rates is highly connected. The TCI index can be decomposed into “TO” and “FROM” measures. The “TO” index measures the extent of transmission of shocks from each instrument to the entire network or system. The “FROM” shows the shocks on an aggregate basis that the instrument (interest rates of different tenors) receives from the entire system of variables. The interest rate with the largest contribution to the “TO” spillover is the OIS with 70.93 (1M), 92.82 (3M), and 85.53(6M). In line with the MTM logic, the OIS, as a risk-free rate indicative of market expectations transmits shocks to other interest rates in the system. These shocks should be absorbed by other interest rates in the system. In line with the MTM logic, the EURIBOR rates are the highest absorber of shocks as shown by the “FROM” measure. However, the “TO” and “FROM” measures do not show the transmission and absorption of shocks of each variable in the system on a net basis. This information is shown by the “NET” indicator. On a net basis, this indicator shows that the OIS are net transmitters of shocks (drivers of other rates) to the system. Additionally, FXIRs (except the 6M maturity category) are net transmitters of shocks in the system.

Figure 3 below presents a network of the interest rates using a graph considered as a system of interest rates with 9 nodes (variables). The nodes represent the variables while the (vertices) directed arrows show the static pairwise directional connectedness. Blue nodes represent net transmitters while the yellow nodes represent net recipients of shocks in the system. Vertices are weighted by averaged net pairwise directional connectedness measures. The thicker the node and vertice, the higher the influence the instrument has on the system. The size of nodes represents weighted average net total directional connectedness. The network plot results are based on a TVP-VAR model with lag length of order one (BIC) and a 10-step-ahead generalized forecast error variance decomposition. The results presented in Figure 3 below are consistent with the information in Table 2.

Figure 3 Network of EUR interest rates



Notes: Blue (yellow) nodes represent net transmitter (net recipient) of shocks. Vertices are weighted by averaged net pairwise directional connectedness measures. The size of nodes represents weighted average net total directional connectedness. The network plot results are based on a TVP-VAR model with lag length of order one (BIC) and a 10-step-ahead generalized forecast error variance decomposition

Table 2 Average Connectedness Measures

	EUR 1M FXIR	EUR 3M FXIR	EUR 6M FXIR	EURIBOR 1M	EURIBOR 3M	EURIBOR 6M	EUR 1M OIS	EUR 3M OIS	EUR 6M OIS	FROM
EUR 1M FXIR	44.27	22.47	13.5	3.27	2.56	2.13	3.71	3.87	4.23	55.73
EUR 3M FXIR	20.8	36.54	20.74	2.58	2.45	1.9	3.98	5.23	5.79	63.46
EUR 6M FXIR	14.4	23.62	36.36	2.69	2.57	2.43	4.15	6.29	7.5	63.64
EURIBOR 1M	6.07	5.03	3.99	28.77	14.9	10.78	10.2	10.75	9.51	71.23
EURIBOR 3M	4.44	4.83	3.64	13.45	25.99	16.41	9.65	11.14	10.45	74.01
EURIBOR 6M	4.16	4.45	4.14	11.33	18.86	25.56	8.93	11.16	11.42	74.44
EUR 1M OIS	4.5	4.27	3.86	5.37	5.46	4.12	39.54	19.34	13.53	60.46
EUR 3M OIS	3.75	5.37	5.13	4.63	5.21	3.6	17.35	31.85	23.1	68.15
EUR 6M OIS	3.76	5.71	6.45	4.35	4.91	3.34	12.96	25.05	33.46	66.54
TO	61.89	75.75	61.46	47.67	56.91	44.72	70.93	92.82	85.53	597.68
Inc. Own	106.16	112.29	97.81	76.43	82.9	70.28	110.47	124.67	118.99	TCI
NET	6.16	12.29	-2.19	-23.57	-17.1	-29.72	10.47	24.67	18.99	66.41
NPDC	5	7	3	1	2	0	4	7	7	

Notes: the results are based on TVP-VAR model with a lag length of order one (BIC) and a 10-step ahead generalised forecast variance decomposition

While the static connectedness measures presented above are useful, they do provide information as regards the evolution of the connectedness of variables. Figure 4 below covers this gap and shows the evolution of the connectedness of EUR interest rates over time. Figure 4 below shows that the connectedness of EUR interest rates is event dependent and elevated during periods of high volatility and market stress. During the 2007-08 GFC connectedness peaked at 80 in October 2008[8]. The TCI was close to 70 all through 2009. This period coincided with the start of the euro sovereign debt crisis (2010) and continued to rise in 2011, rose to 80 in 2013, and stayed above 80 up to 2017. The connectedness was above 80 in March 2020 and peaked at close to 100 in December 2020 during the covid-19 crisis. This is consistent with documented literature which postulates that financial variables are highly interconnected in periods of high volatility and market stress (Chatziantoniou, Gabauer and Stenfors, 2020; Chatziantoniou, Gabauer and Stenfors, 2021).

Further, the literature cites reasons for high volatility connectedness of volatility during market stress in the literature as the fact that these periods are characterised by heightened risk premia. Consequently, most central banks respond by adopting an accommodative monetary policy stance (Chatziantoniou, Gabauer and Stenfors, 2021). During the 2007-08 GFC, EUR interest rates remained elevated due to high credit and liquidity risks. To reduce these risks, according to the European Central Bank (2022), the central bank responded by rate cuts and adopted non-standard measures which included liquidity provision to banks in need, expansion of eligible collateral to access funds from the ECB, lengthening of tenors for refinancing operations, provision of foreign currency liquidity (e.g., US$), and the outright purchases of euro-denominated covered bonds in the Euro area. This eased the liquidity conditions and kept the money market rates low (European Central Bank, 2022). The ECB targeted its support towards the operations of the banking sector[9]. To this effect, the measures could have minimised the risk premia and thereby resulting into high co-movements of interest rates.

Additionally, in response to the covid-19 pandemic, the ECB undertook measures that were aimed at preserving favourable financing conditions during the covid-19 pandemic. The ECB Governing council undertook the following measures to support the financial system: increased the envelope toward the pandemic emergence purchase programme (PEPP), extended the horizon for net purchases (the principal payments reinvestments were extended to end-2023, longer-term refinancing operations were extended, the amount that counterparties could borrow was increased from 50% to 55%, collateral conditions were eased and extended from April 2020 to June 2022, extra emergence assistance was offered by the ECB Governing Council in 2021 (European Central Bank, 2020). These measures did

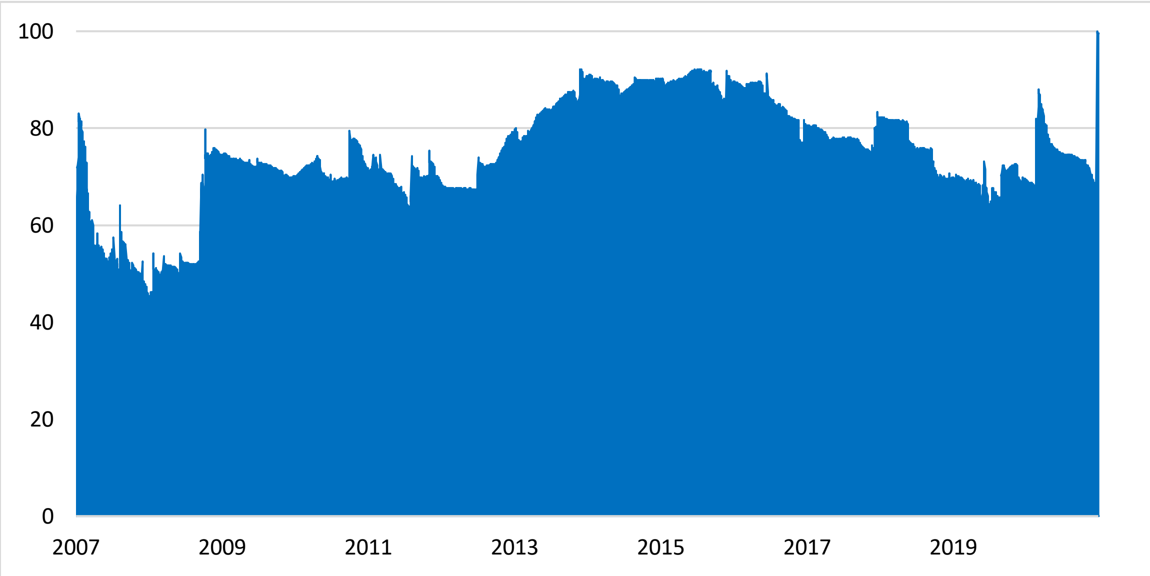
[8] After the collapse of Lehman Brothers on 15 September 2008.

[9] The ECB's approach in crisis periods targets commercial banks' support due to the structure of the system. The ECB's main source of funding for households and corporates is from the banks and constitutes 70%. This is unlike the United States where the banks only account for 25% of the corporates and households' source of funds (Cour-Thimann and Winkler, 2013).

reduce the spreads (risk premia) across money market instruments (Figure 1) and are the probable explanation for the high interconnectedness of the EUR interest rates during the covid-19 crisis.

4.1.2. Total Dynamic Connectedness – EUR interest rates

Figure 4 Total Connectedness Index - EUR interest rates

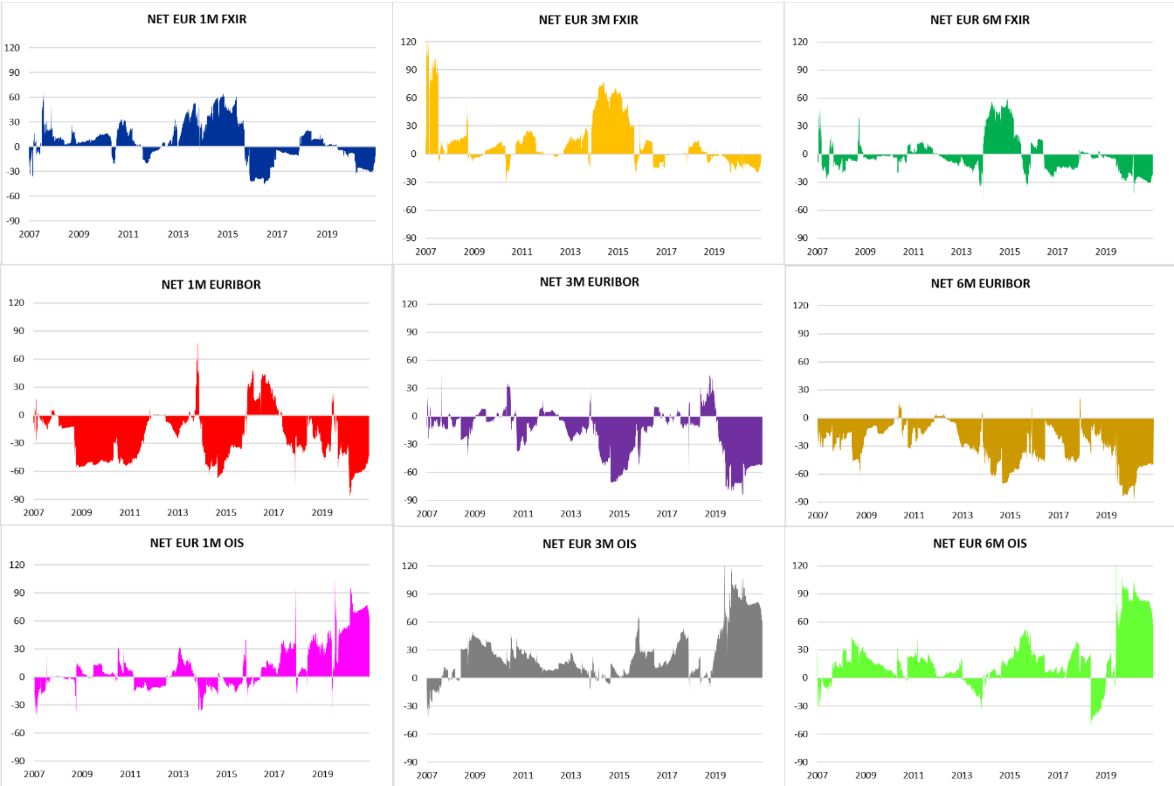


4.1.3. Net Total Directional Connectedness – EUR interest rates

While the TCI in Figure 4 above provides an indication of the size of the connectedness over time, it does not show how each variable transmits shocks to the overall network on a net basis. This information is provided by the net total connectedness index in Figure 5 below. A net transmitter is a major driver (influencer) in the system. If the value is positive, it means that the variable has an impact (influence) on the network. On the other hand, if the value is negative, it means that a variable is an absorber of shocks and has no or limited influence on the other variables in the system.

Figure 5 below shows that FXIRs and OIS recorded positive values most of the time in the period and were, therefore, net transmitters of shocks in the system. This means that shocks were being transmitted from the FXIRs and OIS, with the EURIBOR rates as shock absorbers in the system in line with the MTM logic. According to the MTM logic, the first stage of central banks' transmission of monetary policy is short-term rates and market expectations which should be transmitted to money and credit, asset prices, bank rates, and exchange rates before being transmitted to the real economy (European Central Bank, 2021).

Figure 5 Net Total Directional Connectedness – EUR interest rates



Notes: The results are based on a TVP-VAR model with a lag length of order one (BIC) and a 10-step-ahead generalized forecast error variance decomposition

4.1.4. Net Pairwise Dynamic Connectedness - EUR interest rates

While the net total directional connectedness provides insights on which instruments across maturities categories are net transmitters and recipients of shocks over time in the system, it does not show the direction of shocks between variables (bi-directional relationship) in the system. Figure 6 below shows this detail and presents the bi-directional interrelations of variables over time. It shows the transmission of shocks across maturity categories of the interest rates, as well as bi-directional relationships between interest rates.

Commencing with the transmission of shocks across maturity categories, the MTM logic requires that shocks should be transmitted from the short-term to the medium and long-end part of the money market yield curve. Particularly, central bank announcements (1M) should be transmitted to other parts of the money market yield.

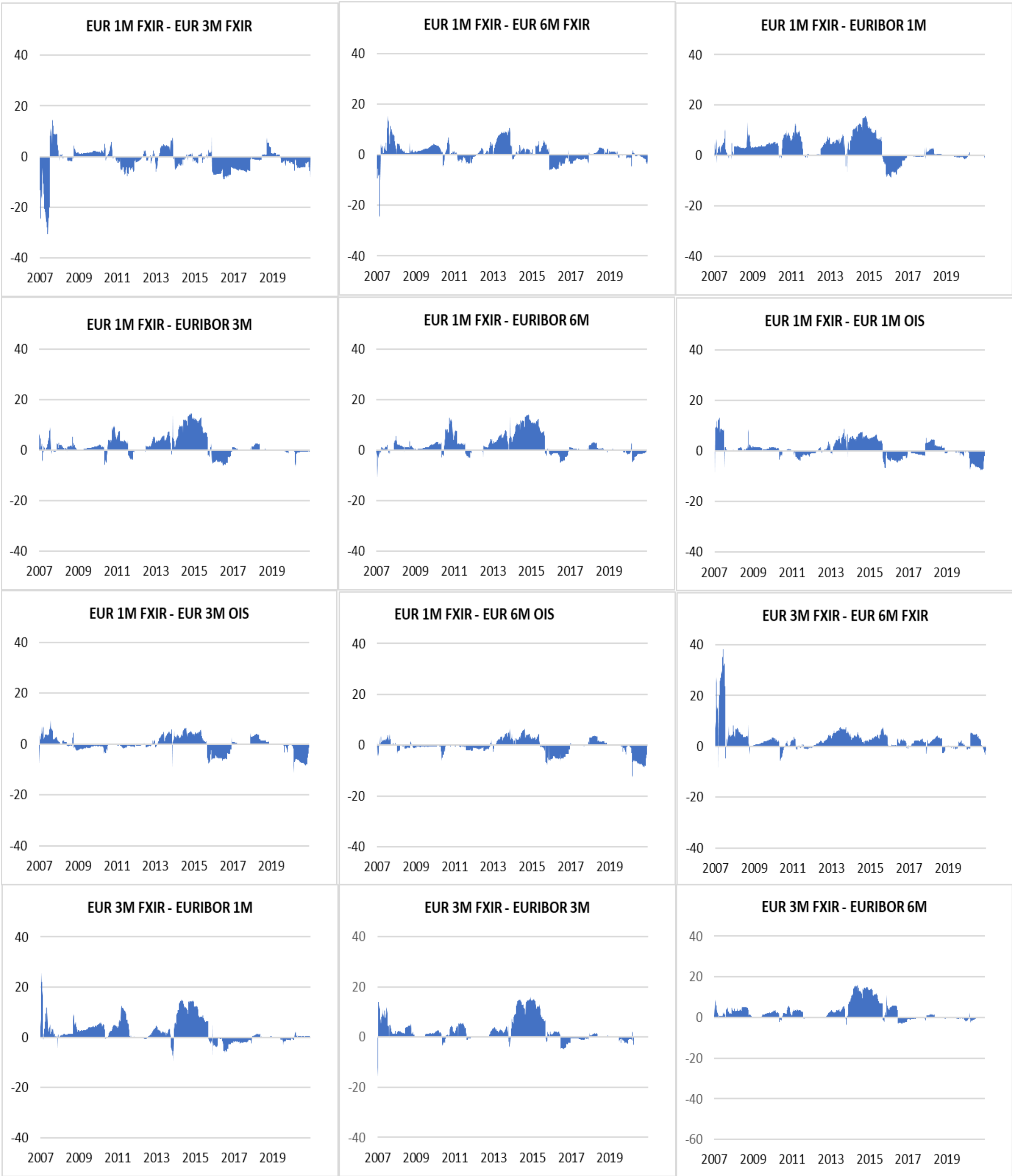
The findings show that the spillovers for the EUR OIS maturity categories assume mixed roles over time. The 1M, 3M, and 6M maturity categories assume both a net transmitting and net receiving role in the period under review. While the 3M dominates the transmission of shocks to the 6M maturity categories in line with the MTM logic, a challenge exists in the transmission from the 1M to the 3M and 6M maturities categories, as the latter dominate transmission of shocks to the former. This represents a breakdown in the transmission of shocks from 1M to 3M and 6M tenors. Turning to EUR FXIRs, in line with the MTM logic, the 1M and 3M tenors dominate spillovers to the 6M maturity category. However, like the EUR OIS, the transmission of shocks between the short-term (1M) and long-term (3M) assume mixed roles over time. Similarly, in the unsecured interbank market (EURIBOR rates), the propagation of shocks across maturities assumes a mixed role over time. Specifically, while the 1M and 3M dominate transmission to the 6M maturity category is in line with the MTM logic, the transmission of shocks from the (1M) to the (3M) assumes a mixed role.

Looking at the specificities of bi-directional relationships of instruments (FXIRs, OIS, and EURIBOR rates) over time, the analysis shows the transmission of shocks from OIS, an indication of market expectations to the unsecured market segment (EURIBOR) was in accordance with the MTM logic. The unsecured interbank market (EURIBOR rates) reacted to market expectations (OIS) most of the time. During the 2007-08 GFC, Euro sovereign debt crisis, and covid-19 crisis, as part of forward guidance, it seems ECB intentions were clearly announced. For example, as reported by Reuters (2011), during the European sovereign debt crisis, money market dealers expected the ECB to provide funds to banks for as long as they needed liquidity. Consequently, EURIBOR spreads were lower at a range of 20-25 basis points from 110 basis points recorded end of 2008.

However, the relationship between FXIRs and OIS shows that the two instruments assume mixed roles, with the former not responding to market expectations during the 2007/2008 GFC and 2013 – 2015 in the respective 3M and 6M maturity categories. The challenge of the foreign exchange swap market in reacting to market expectations in some periods could emanate from the fact that despite the global response in adopting swap lines to cover the USD shortages, market participants may not have been confident that this measure will adequately address the liquidity strains. This is reflected in persistent CIP deviations even post the 2007-08 GFC which is an indication of risk premia in the market (Chatziantoniou, Gabauer and Stenfors, 2020). For example, the cross currency basis a metric used to measure funding stress has persistently deviated from zero since the 2007-08 GFC (Borio et al., 2016).

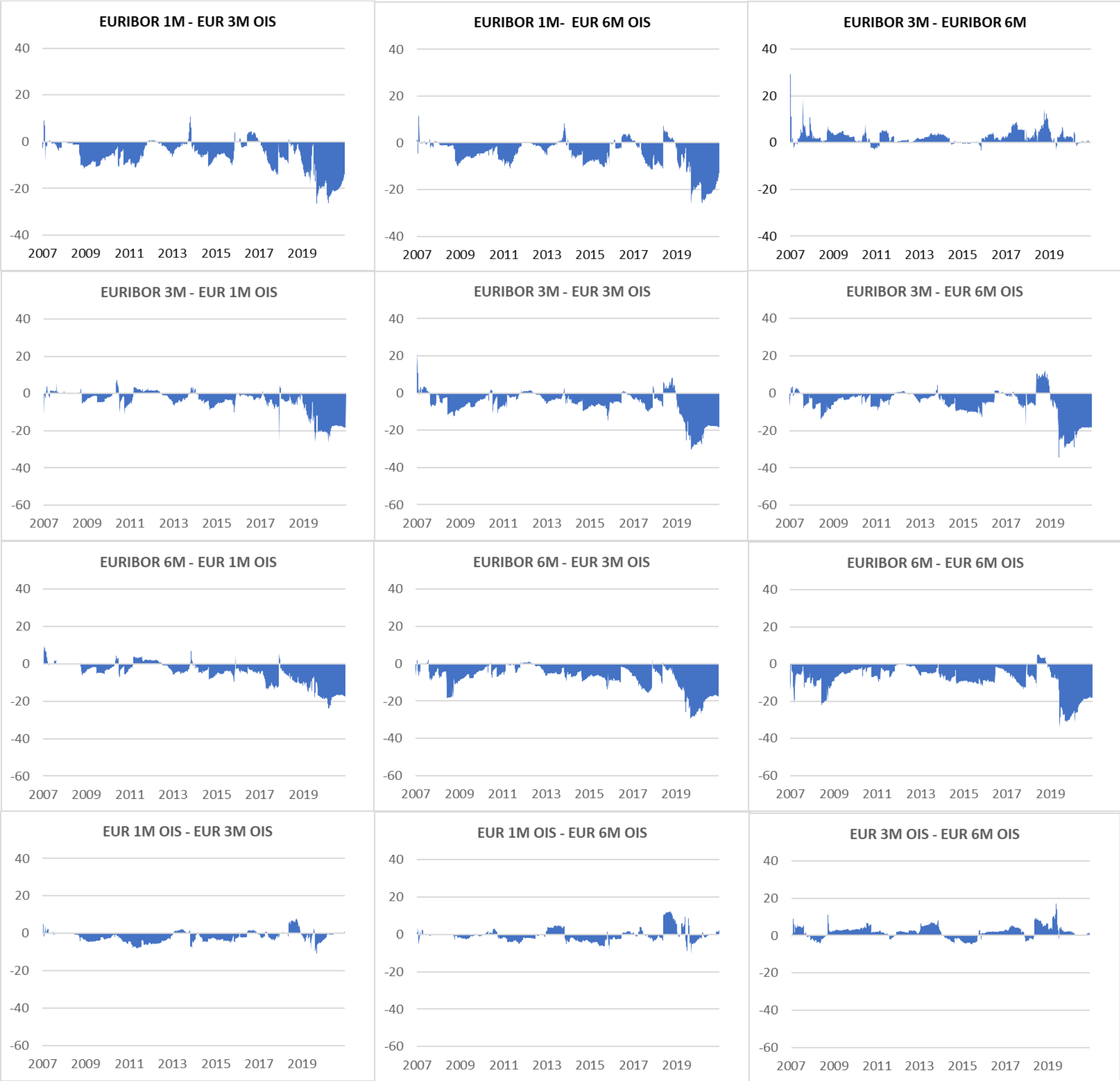
As regards the bi-directional relationship between FXIRs and EURIBOR rates, the two interest rates assumed mixed roles over time. The transmission of shocks from the unsecured interbank segment (EURIBOR) to FXIRs emanated from the liquidity strains of the USD in the global financial system. The main driver of the foreign exchange swap market was the developments in the USD funding market. During the 2007-08 GFC, the heightened credit risk, especially by non-US financial institutions, including European financial institutions led to USD shortages and therefore reluctance to lend the USD as most participants were hoarding the USD. Consequently, non-US financial institutions resorted to converting the EUR into USD Liquidity through foreign exchange swaps. This shock in the unsecured interbank market spilled over to the foreign exchange swap market (European Central Bank, 2007; Baba, Packer and Nagano, 2008). This shock in the unsecured interbank market spilled over to the foreign exchange swap market (European Central Bank, 2007; Baba, Packer and Nagano, 2008). While there was a period when shocks spillover from the unsecured market to the foreign exchange swap market, the latter (FXIRs) dominated the transmission of shocks to the former (EURIBOR rates) from 2007 to 2015. The reverse transmission of shocks from FXIRs to EURIBOR rates is possible due to the liquidity strains that were present in the foreign exchange swap market during this period. A liquid foreign exchange swap market can absorb demand and supply shocks from the unsecured interbank market by diversifying the effects of shocks to other domestic currency denominated markets. If there are liquidity strains in the foreign exchange swap market, it makes it difficult to find sellers of the euro which is likely to exert pressure on the unsecured interbank market. Consequently, the strains can be transmitted to the unsecured interbank market (Imakubo, Kimura and Nagano, 2008).

Figure 6 Net Pairwise Dynamic Connectedness – EUR interest rates



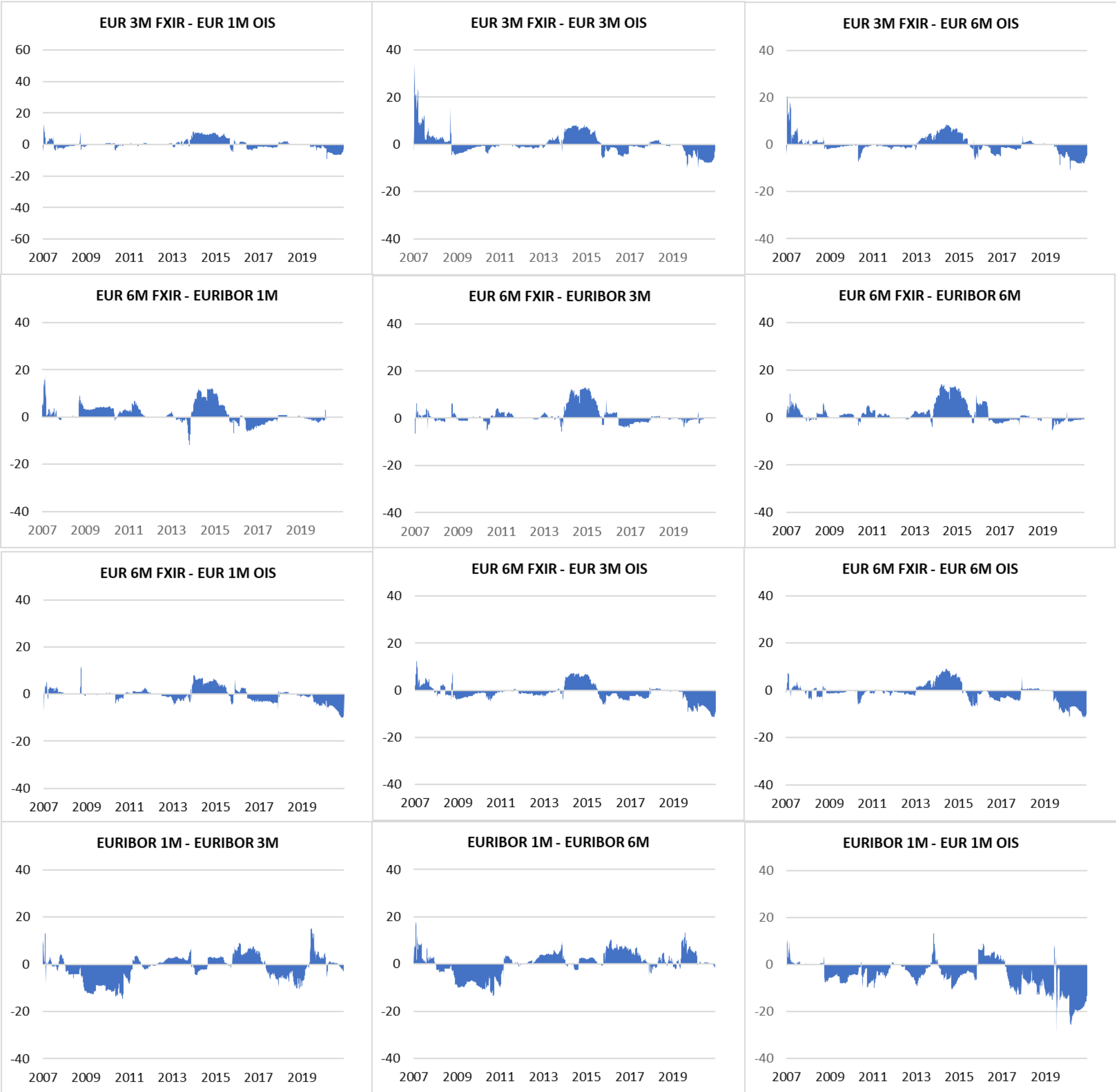
Notes: The results are based on a TVP-VAR model with lag length of order one (BIC) and a 10-step-ahead generalized forecast error variance decomposition.

Figure 6 Net Pairwise Dynamic Connectedness – EUR interest rates



Notes: The results are based on a TVP-VAR model with lag length of order one (BIC) and a 10-step-ahead generalized forecast error variance decomposition.

Figure 6 Net Pairwise Dynamic Connectedness – EUR interest rates



Notes: The results are based on a TVP-VAR model with lag length of order one (BIC) and a 10-step-ahead generalized forecast error variance decomposition.

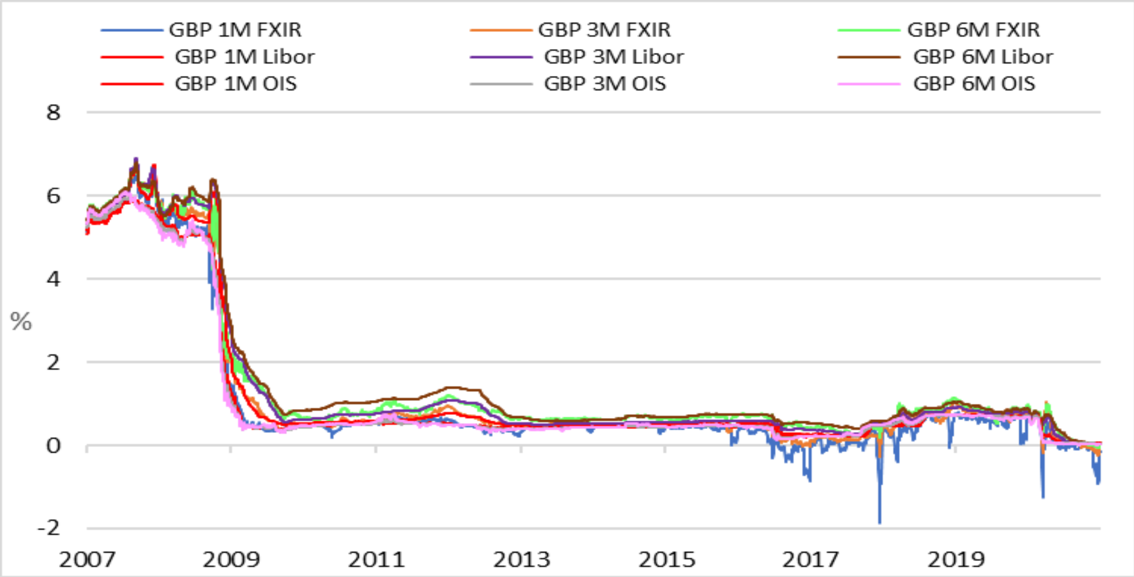
4.2. GBP interest rates

Figure 7 below shows GBP interest rates for the period, 2/1/2007 – 31/12/2020. Noteworthy is that the interest rates remained high during the 2007-08 GFC. This is because the United Kingdom was not insulated from the global challenges that arose from the US Sub-Prime mortgage in the summer of 2007. This year, a run was declared on a British Bank, Northern Rock after it faced severe liquidity challenges. These liquidity challenges did not spare financial institutions including Lehman Brothers which collapsed in September 2008 (Bank of England, 2022a).

To alleviate the credit risks, and the subsequent drying up of liquidity in the interbank market, like other central banks, the Bank of England (BOE) reduced its official rate (Bank Rate) five times in 2008. It was reduced as follows: by 25 basis points in February 2008 (5.25%), 25 basis points in April 2008 (5%), 50 basis points in October 2008 (4.5%), 150 basis points in November 2008 (3%), 100 basis points in December 2008 (2%). In 2009, the official rates was reduced three (3) times, by 50 basis points in January 2009 (1.5%), 50 basis points in February 2009 (1%), and by 50 basis points in March 2009 (0.5%). This rate was maintained at 0.5% up to 4 August 2016 after the Brexit Referendum (23 June 2016) when the rate was reduced to 0.25%.

Additionally, BOE adopted quantitative which involved the purchase of UK government bonds or corporate bonds from financial institutions and pension funds (Bank of England, 2022c). This kept the interest rates low post the 2007-08 GFC. Bank of England only adopted a tight monetary policy stance on 2 November 2017 when the rates was increased to 0.5% and a further increase to 0.75% on 2 August 2018. However, the tight monetary stance was reversed in March 2020 when the BOE responded to mitigate the risk premia arising from the covid – 19 crisis. The BOE reduced the official rate by 50 basis points to 0.25% on 11 March 2020 and to 0.1% on 19 March 2020.

Figure 7 GBP Interest rates, 2/1/2007 – 31/12/2020



Source: Bloomberg and author's calculations

Notes: GBP interest rates represent foreign exchange swaps implied rates (GBP 1M FXIR, GBP 3M FXIR, and GBP 6M FXIR), LIBOR rates (GBP 1M LIBOR, GBP 3M LIBOR, and GBP 6M LIBOR), and Overnight index swaps (GBP 1M OIS, GBP 3M OIS, and GBP 6M OIS). The implied rates are calculated using the USD as the funding currency in the GBP/USD currency pair, the 1M,3M, and 6M USD LIBOR rates are used to represent the respective USD interest rates.

Table 3 below shows the summary statistics for GBP interest rates for the period 2/1/2007-31/12/2020. The statistics show that the 3M maturity categories have the highest variance for the GBP LIBOR rates and GBP FXIRs. The 6M tenor has the highest variance among the OIS. The Elliot, Rothenberg, and Stock (ERS) shows that all GBP series are non-stationary (Elliot et. al., 2016). To avoid spurious regression, the series are differenced are I(1) (Figure 8). Additionally, the skewness and kurtosis series in Table 3 indicate that the series are not normally distributed (D'Agostino, 1970; Jarque and Bera 1980; Anscombe and Glynn, 1983). Further, Q(20) and Q2 (20) are the weighted Ljung-Box statistic tests for serial correlation in returns and squared series show evidence of autocorrelation in the series (Fisher and Gallagher 2012). The characteristics of the data show that the TVP-VAR model is an appropriate economic analysis framework.

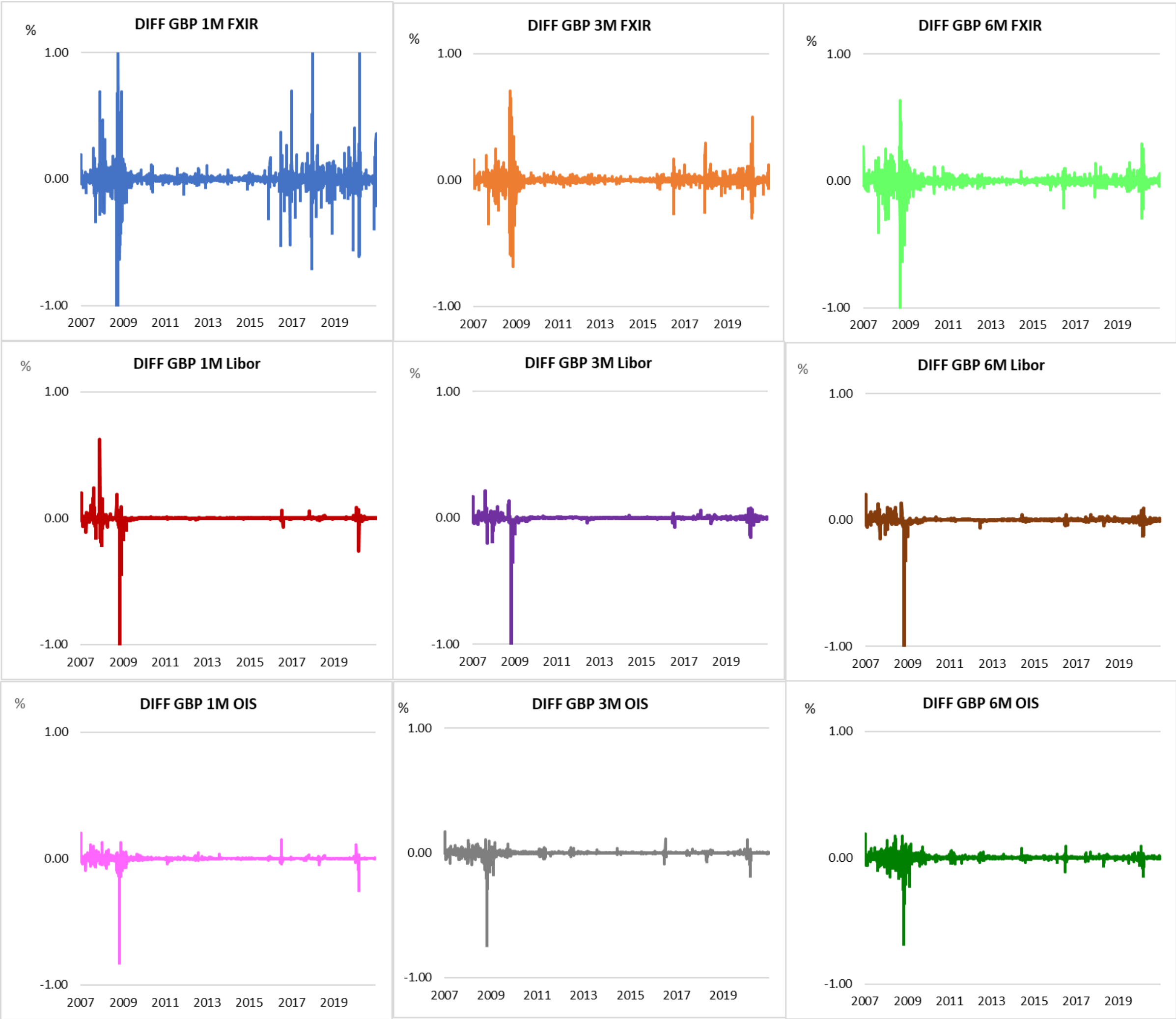
Table 3 Summary statistics - GBP Interest rates

	GBP 1M FXIR	GBP 3M FXIR	GBP 6M FXIR	GBP 1M LIBOR	GBP 3M LIBOR	GBP 6M LIBOR	GBP 1M OIS	GBP 3M OIS	GBP 6M OIS
Observations	3,526	3,526	3,526	3,526	3,526	3,526	3,526	3,526	3,526
Mean	1.0810	1.2504	1.4261	1.2493	1.3932	1.5388	1.1104	1.1058	1.1091
Variance	3.2036	3.2265	3.1531	3.2065	3.3659	3.2561	2.8090	2.8083	2.8093
Skewness	2.07***	2.06***	2.04***	2.07***	2.00***	1.96***	2.12***	2.14***	2.16***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Ex.Kurtosis	2.590***	2.507***	2.417***	2.461***	2.239***	2.121***	2.679***	2.758***	2.862***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
JB	3499.190***	3424.881***	3298.686***	3397.283***	3082.407***	2910.937***	3705.870***	3814.786***	3948.838***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
ERS	0.167	0.584	0.987	0.673	0.767	0.927	1.056	1.057	1.163
	(0.8670)	(0.5600)	(0.3240)	(0.5010)	(0.4430)	(0.3540)	(0.2910)	(0.2900)	(0.2450)
Q(10)	19133.94***	19236.92***	19247.77***	19271.75***	19285.58***	19281.86***	19271.72***	19261.93***	19251.99***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Q2(10)	19131.82***	19225.01***	19237.93***	19244.47***	19276.71***	19277.39***	19284.07***	19271.50***	19256.21***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)

Source: Bloomberg and author’s calculations

Notes: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$. ( ) denote standard errors. The D’Agostino (1970) and Anscombe and Glynn (1983) statistics are used for skewness and kurtosis. JB (Jarque and Bera 1980) is the test for Normality, ERS unit root test (Stock et al. 1996) tests for stationarity, Q(20) and Q2 (20) are the weighted Ljung-Box statistic for serial correlation in the returns and squared series (Fisher and Gallagher 2012), respectively

Figure 8 First differenced GBP interest rates

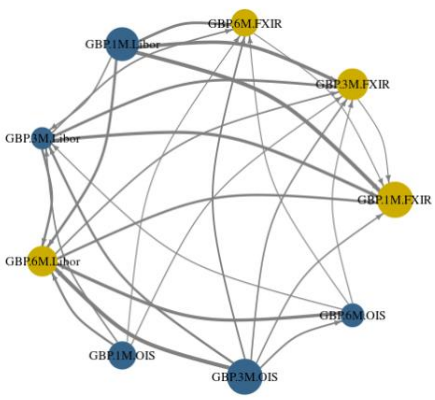


Notes: EUR differenced rates are stationary at a 1 percent level of significance.

4.2.1. Static volatility connectedness – GBP interest rates

The TCI in Table 4 below shows that the network of GBP interest rates is highly connected (70.25) as the index is close to 100. This means that a shock in one variable will cause adjustments in other variables. When compared to the EUR interest rates with the TCI at 66.41, the GBP interest rates are highly connected. The “TO” and “NET” indicators in Table 4 show that the OIS and GBP LIBOR rates (1M and 3M) have a high influence on the transmission of shocks to GBP interest rates. This means that, on average, GBP interest rates react to a shock in OIS (market expectations). On the other hand, the “FROM” indicator shows that GBP FIXRs and 6M GBP LIBOR have a large influence on the system. This is still confirmed by the “NET” indicator that shows that GBP FXIRs and the 6M GBP LIBOR are net recipients of shocks in the system. The results in Table 4 are consistent with Figure 9.

Figure 9 Network of GBP Interest rates



Notes: Blue (yellow) nodes represent net transmitter (net recipient) of shocks. Vertices are weighted by averaged net pairwise directional connectedness measures. The size of nodes represents weighted average net total directional connectedness. The network plot results are based on a TVP-VAR model with lag length of order one (BIC) and a 10-step-ahead generalized forecast error variance decomposition.

Table 4 Average Dynamic Connectedness - GBP interest rates

	GBP 1M FXIR	GBP 3M FXIR	GBP 6M FXIR	GBP 1M LIBOR	GBP 3M LIBOR	GBP 6M LIBOR	GBP 1M OIS	GBP 3M OIS	GBP 6M OIS	FROM others
GBP 1M FXIR	36.59	15.47	9.65	9.41	7.83	6.33	5.35	4.98	4.39	63.41
GBP 3M FXIR	13.96	30.4	14.34	8.86	8.11	6.53	5.65	6.61	5.54	69.6
GBP 6M FXIR	8.6	14.56	31.12	8.34	7.39	6.09	7.08	8.08	8.73	68.88
GBP 1M LIBOR	4.53	4.5	4.44	29.39	17.3	12.62	11.67	8.84	6.71	70.61
GBP 3M LIBOR	3.86	4.52	4.71	19.22	25.88	16.9	8.88	8.89	7.14	74.12
GBP 6M LIBOR	3.05	4.14	5	15.89	19.92	25.42	7.7	9.74	9.14	74.58
GBP 1M OIS	4.61	4.51	5.91	11.92	8.04	6.06	31.11	16.33	11.51	68.89
GBP 3M OIS	3.5	5.03	5.88	8.79	7.21	6.17	15.88	28.22	19.32	71.78
GBP 6M OIS	3.57	4.61	7.51	7.87	6.65	6.27	12.54	21.41	29.57	70.43
TO others	45.68	57.33	57.44	90.31	82.45	66.96	74.74	84.89	72.49	632.29
Inc. own	82.27	87.73	88.57	119.7	108.34	92.38	105.86	113.11	102.06	TCI
NET	-17.73	-12.27	-11.43	19.7	8.34	-7.62	5.86	13.11	2.06	70.25
NPDC	8	6	7	1	4	5	2	0	3	

Notes: the results are based on TVP-VAR model with a lag length of order one (BIC) and a 10-step ahead generalised forecast variance decomposition

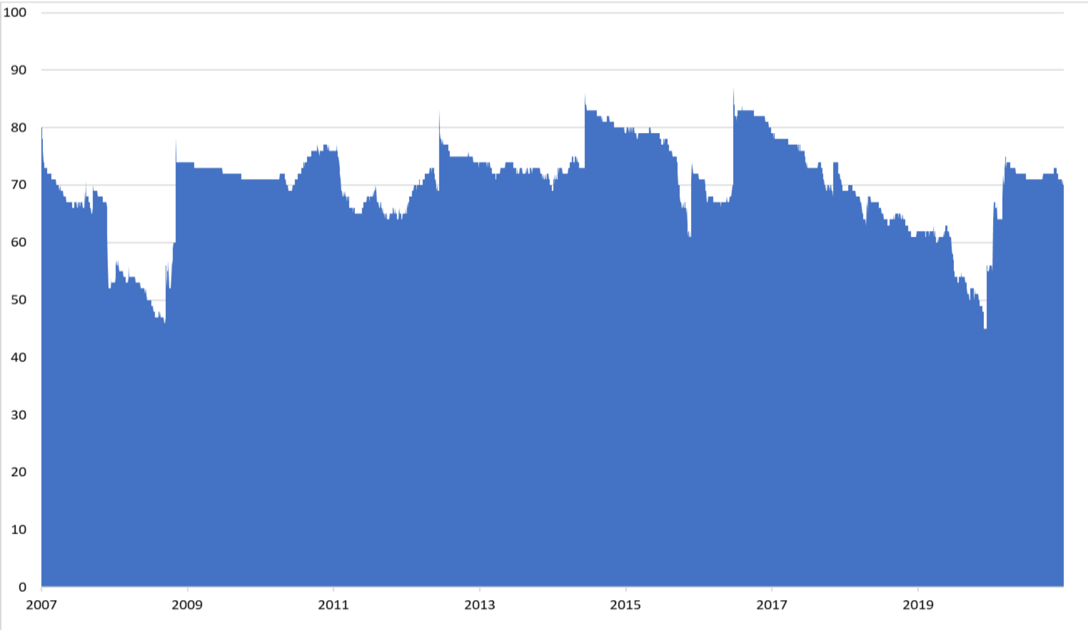
4.2.2. Total Dynamic Connectedness – GBP interest rates

While the static analysis above shows GBP interest rates are highly correlated as indicated by the TCI, it does not show how it varies over time. Turning to its evolution, Figure 10 shows that connectedness varies over time and reacts to market events. As already alluded above Chatziantoniou, Gabauer and Stenfors (2021) highlight that central bank interventions aimed at reducing the risk premia in the money market increase the interconnectedness of the financial market variables, particularly interest rates. In particular, the TCI peaked at 78 on 6 November 2008 after the collapse of Lehman Brothers in September 2008. Turning to the BOE's response to the 2007-08 GFC, like many central banks, the BOE, responded to crises (reduce the risk premia in the interbank market) by adopting the accommodative monetary policy, quantitative easing, and forward guidance. This kept interest rates low post the 2007-08 GFC. In 2008, BOE reduced its official rate (Bank Rate) five times. It was reduced as follows: by 25 basis points in February 2008 (5.25%), 25 basis points in April 2008 (5%), 50 basis points in October 2008 (4.5%), 150 basis points on 6 November 2008 (3%), 100 basis points in December 2008 (2%). Notable is that the interconnectedness peak on 6 November 2008 coincides with the highest policy cut from 4.5% to 3% (150 basis points) on 6 November 2008.

Connectedness remained elevated (above 70) from November 2008 to January 2011. The next peak was recorded in 15 June 2012 (83) and stayed above 70 up to June 2014 before recording peaks on 13 June 2014 (86). During this time, BOE continued with its policy cuts. In 2009, the official rates were reduced three (3) times, by 50 basis points in January 2009 (1.5%), 50 basis points in February 2009 (1%), and by 50 basis points in March 2009 (0.5%).

High interconnectedness (a peak) was recorded on 29 June 2016 after the Brexit Referendum which took place on 23 June 2016. During this time, BOE maintained the official rate at 0.5% up to 4 August 2016 after the Brexit Referendum (23 June 2016) when the rate was reduced to 0.25%. Additionally, high interconnectedness was recorded in March and December 2020 during the covid-19 crisis. The BOE responded to the covid-19 crisis by reducing the official rate by 50 basis points to 0.25% on 11 March 2020 and to 0.1% on 19 March 2020. Additionally, BOE adopted quantitative easing which involved the purchase of UK government bonds or corporate bonds from financial institutions and pension funds (Bank of England, 2022c).

Figure 10 Dynamic Total Connectedness – GBP interest rates

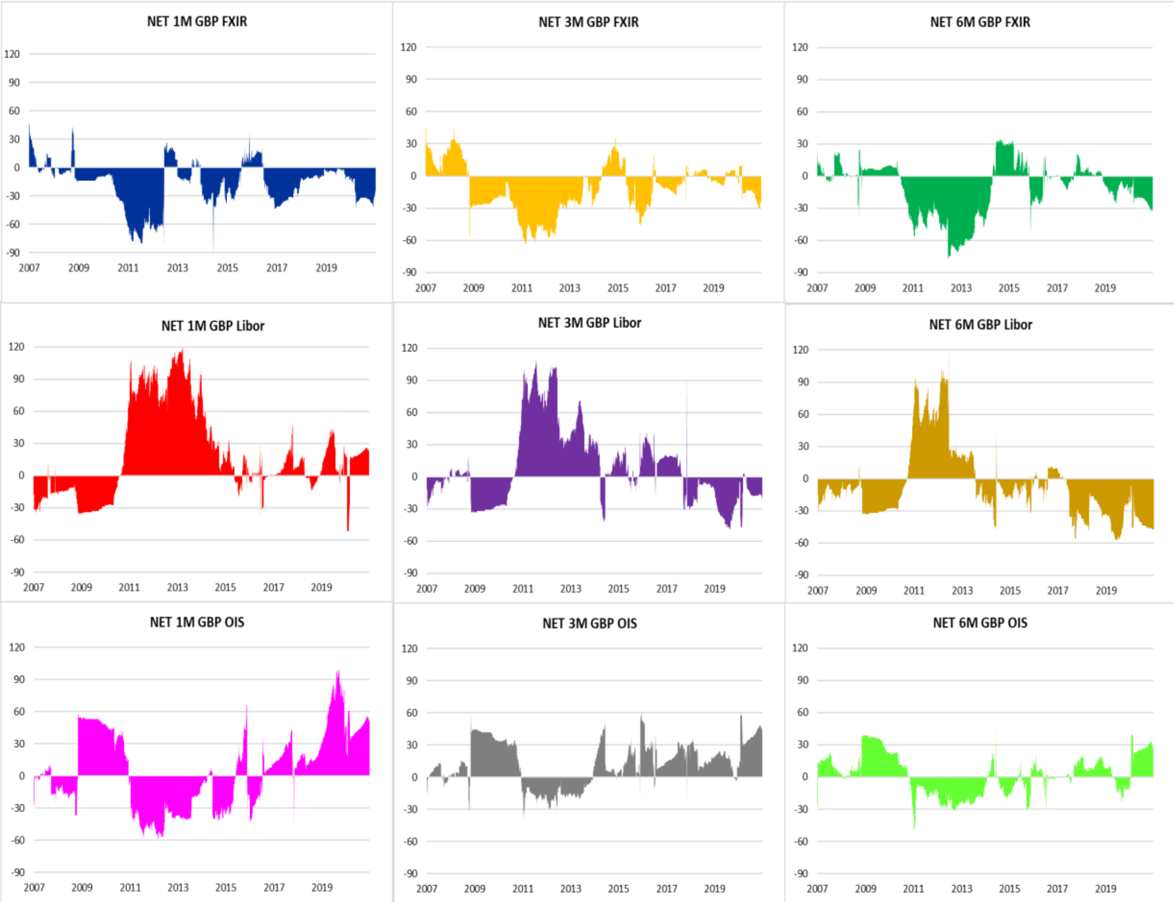


Notes: The Total Connectedness Index is based on a TVP-VAR model with a lag length of order one and a 10-step-ahead generalized forecast error variance decomposition based on the Bayesian Information Criterion (BIC).

4.2.3. Net Total Directional Connectedness – GBP interest rates

The TCI shows aggregate connectedness of interest rates over time and does not show the extent of transmission of individual GBP interest rates to the system on a net basis. This detail is shown in Figure 11 below. Notable is that GBP FXIRs assume mixed spillover roles over time but dominated the transmission of shocks to the system during the 2007-08 GFC but assume a net receiving role post-2009. On the other hand, 1M GBP LIBOR rate assumes a net transmitting role from 2010 onwards. The 3M GBP LIBOR rate also assumes a net transmitting role during the GFC (2007-2009) and 2010-2017 but assumes a net receiving role from September 2017 onwards. The 6M GBP LIBOR assumed the net transmitting role 2010-2013 but assumed a net receiving role during the GFC and post September 2013. Generally, market expectations transmitted shocks to the system of variables. However, it seems there were challenges in other interest rates reacting to market expectations in some periods. The 1M was a net recipient of shocks from 2011-2013, 3M from 2011-2015, 6M from 2011-2014. To get a clearer picture of the transmission of shocks, in particular, bi-directional relationships between GBP interest rates, Figure 12 below shows this information.

Figure 11 Net Total Directional Connectedness – GBP interest rates



Notes: The results are based on a TVP-VAR model with lag length of order one (BIC) and a 10-step-ahead generalized forecast error variance decomposition

4.2.4. Net Pairwise Dynamic Connectedness – GBP interest rates

For brevity purposes, this section only highlights key and relevant observations of the results. Turning to the transmission of shocks across maturity categories. First, the MTM across maturity categories for OIS show that while all maturity categories assume mixed roles over time, the 3M dominates transmission to the 6M tenor. Similar to EUR interest rates, there seems to be a disconnect between the transmission of the central bank announcements (1M) to the 3M maturity category. Further, the 1M and 6M maturity assume mixed roles in the transmission of shocks.

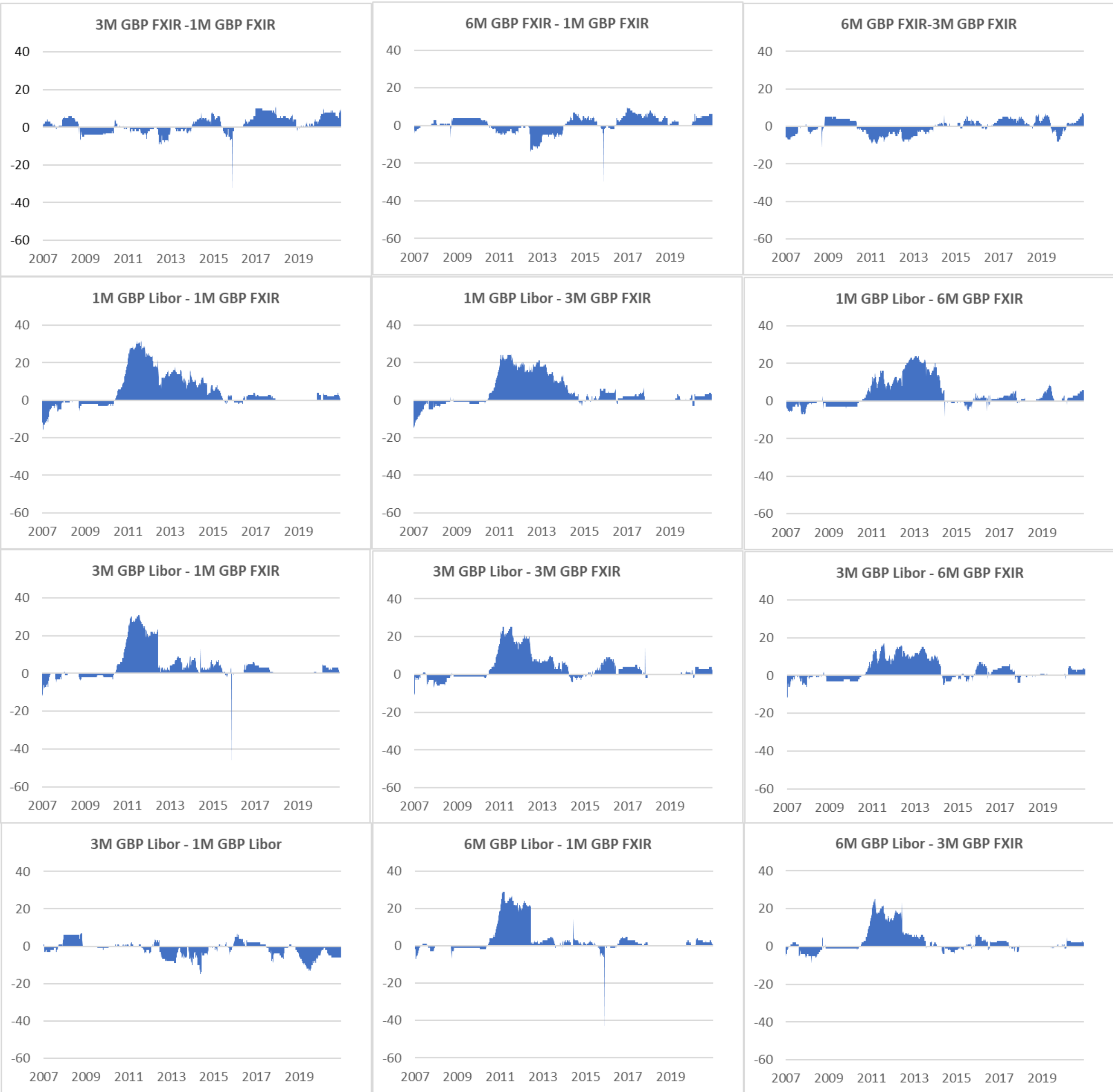
As regards GBP FXIRs, there is a mixed role in the transmission across the short-term, medium-term, and long-term parts of the money market yield curve. Specifically, in line with the MTM logic, the central bank announcements (1M) dominate transmission to the 3M and 6M categories prior to 2014. However, this relationship is disconnected post-2014, as the 3M and 6M dominate their influence on 1M. Similarly, the 3M maturity category dominates its influence on the 6M prior to 2014 but the direction of shocks changes post-2014.

As regards the GBP LIBOR rates, it seems the maturity categories assume mixed roles in transmitting shocks in the system. In line with the MTM logic, the 1M dominates its influence on the 3M tenor and the 6M maturity category. Additionally, the 3M maturity category dominates transmission to the 6M tenor.

Turning to the bi-directional relationship between the OIS (market expectations) and GBP LIBOR rates and GBP FXIRs. Starting with the bi-directional relationship between the OIS and GBP LIBOR rates. The OIS dominate the transmission of shocks to the GBP LIBOR rates, except for the period 2011-2014. This is because it was noted that the spread LIBOR-OIS spread diverged from the onset of the 2007-08 GFC. As noted by Stenfors (2021, pp 10) states, if the LIBOR and equivalent IBORs deviate significantly from the risk-free rate derived from the central bank official rate (OIS), this implies that the MTM is highly impaired. Further, the possibility of measurement error of GBP LIBOR rates is a possible plausible explanation of the reverse transmission of shocks from OIS to GBP LIBOR rates. As regards to the relationship between OIS and FXIRs, while the 3M OIS dominates transmission to the 3M GBP FIXRs, the 1M OIS and 1M GBP FXIRs, 6M OIS and 6M GBP FXIRs assume mixed roles overtime in terms of transmission of shocks.

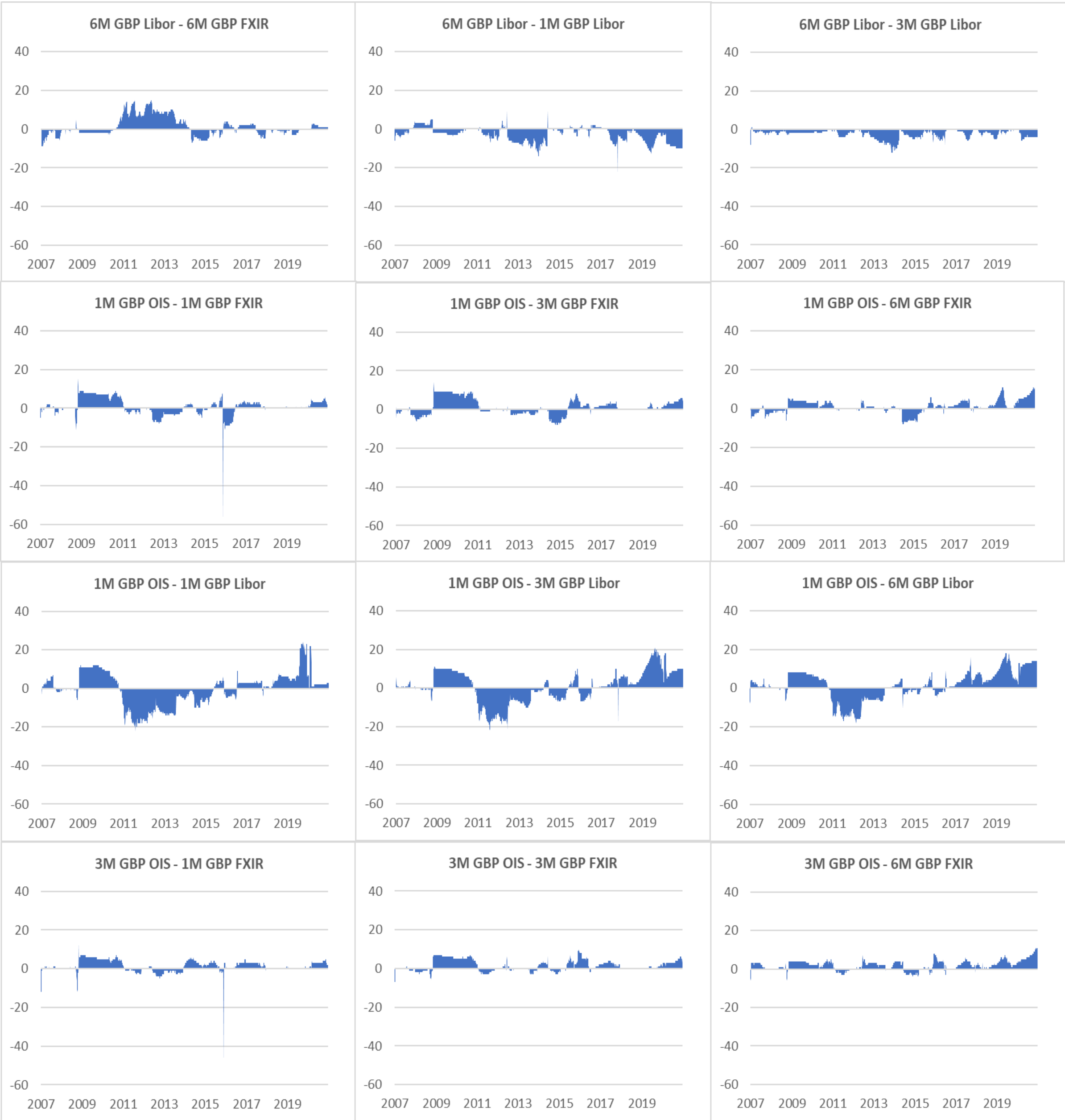
Turning to the relationship between FXIRs and GBP LIBOR rates, it is noted that the foreign exchange swap market (FXIRs) dominates its influence on the unsecured market segment (GBP LIBOR rates) during the 2007-08 GFC, the latter dominates transmission to the former post-2011. Similar to EUR interest rates, as explained above, this evidence is consistent with the fact that the global USD funding challenges in foreign exchange swap markets spilled over to the GBP unsecured money market segments during the GFC (Baba, Packer and Nagano, 2008). The reverse transmission of shocks from GBP LIBOR rates to FXIRs is in line with Aldaros, Ehlers and Eren (2019) who highlight market stress such as drying up of liquidity in one market creates substitution challenges for banks to source funds in an alternative money market. Such a shock spills over to other money markets.

Figure 12 Net Pairwise Dynamic Connectedness – GBP interest rates



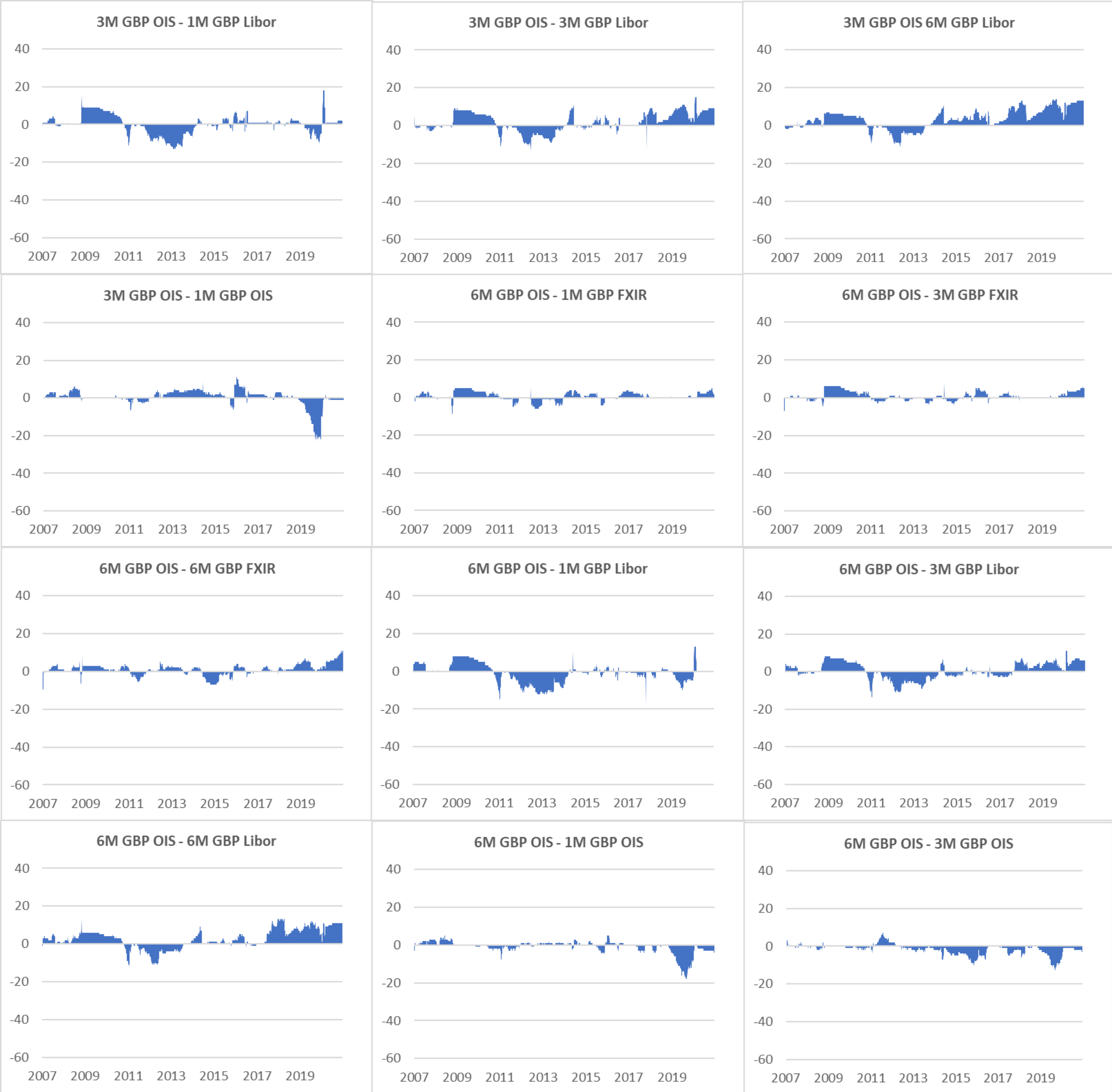
Notes: The results are based on a TVP-VAR model with lag length of order one (BIC) and a 10-step-ahead generalized forecast error variance decomposition

Figure 12 Net Pairwise Dynamic Connectedness – GBP interest rates



Notes: The results are based on a TVP-VAR model with lag length of order one (BIC) and a 10-step-ahead generalized forecast error variance decomposition

Figure 12 Net Pairwise Dynamic Connectedness – GBP interest rates



Notes: The results are based on a TVP-VAR model with lag length of order one (BIC) and a 10-step-ahead generalized forecast error variance decomposition

4.3. JPY interest rates

Figure 13 below shows JPY interest rates for the period, 2/1/2007 – 31/12/2020. Unlike other major economies, Japan had been experiencing a crisis commonly referred to as the 'lost decades' since 1990. This is a period characterised by slow growth, deflation (negative inflation), and a negative output gap. To this effect, to address this, Japan is one of the first economies to adopt unconventional monetary policy and including reducing policy rates to zero and recently to negative rates (Egea and del Río López, 2021). Compared to other markets, the rates were elevated but close to zero during the 2007-08 GFC.

The notable spike in the implied rates especially the JPY 1M (-5.4171%) on 18 September 2008, follows the collapse of the Lehman Brothers on 15 September 2008. This resulted into a dry up of USD funding and therefore banks resorted to the foreign exchange swap market to source the USD funding. It was therefore more expensive to borrow USD from the foreign exchange market using the Yen, a premium was added due to the heightened perceived creditworthiness on the Japanese counterparties (Stenfors, 2019). Another peak of the implied rates is recorded on 19 March 2020, during the covid crisis.

Figure 13 JPY Interest rates

Source: Bloomberg and author's calculations

Notes: JPY interest rates represent foreign exchange swap implied rates (JPY 1M FXIR, JPY 3M FXIR, and JPY 6M FXIR), LIBOR rates (JPY 1M LIBOR, JPY 3M LIBOR, and JPY 6M LIBOR) and Overnight index swaps (JPY 1M OIS, JPY 3M OIS, and JPY 6M OIS). The implied rates are calculated using the USD as the funding currency in the USD/JPY currency pair, the 1M, 3M, and 6M USD LIBOR rates are used to represent the respective USD interest rates.

Table 5 below shows the summary statistics for JPY interest rates for the period 2/1/2007-31/12/2020. The statistics show that the 1M maturity category has thee the highest variance for the foreign exchange swaps (implied rates). On the other hand, the 3M maturity categories have the highest variance for JPY LIBOR rates and JPY FXIRs. The Elliot, Rothenberg, and Stock (ERS) shows that all JPY series but the 1M JPY Implied rate are non-stationary (Elliot et. al., 2016). To avoid spurious regression, the non-stationary series are differenced are I(1) (Figure 14). Additionally, the skewness and kurtosis series in Table 3 indicate that the series are not normally distributed (D'Agostino, 1970; Jarque and Bera 1980; Anscombe and Glynn, 1983). Further, Q(20) and Q2 (20) are the weighted Ljung-Box statistic tests for serial correlation in returns and squared series show evidence of autocorrelation in the series (Fisher and Gallagher 2012). The characteristics of the data show that the TVP-VAR model is an appropriate economic analysis framework.

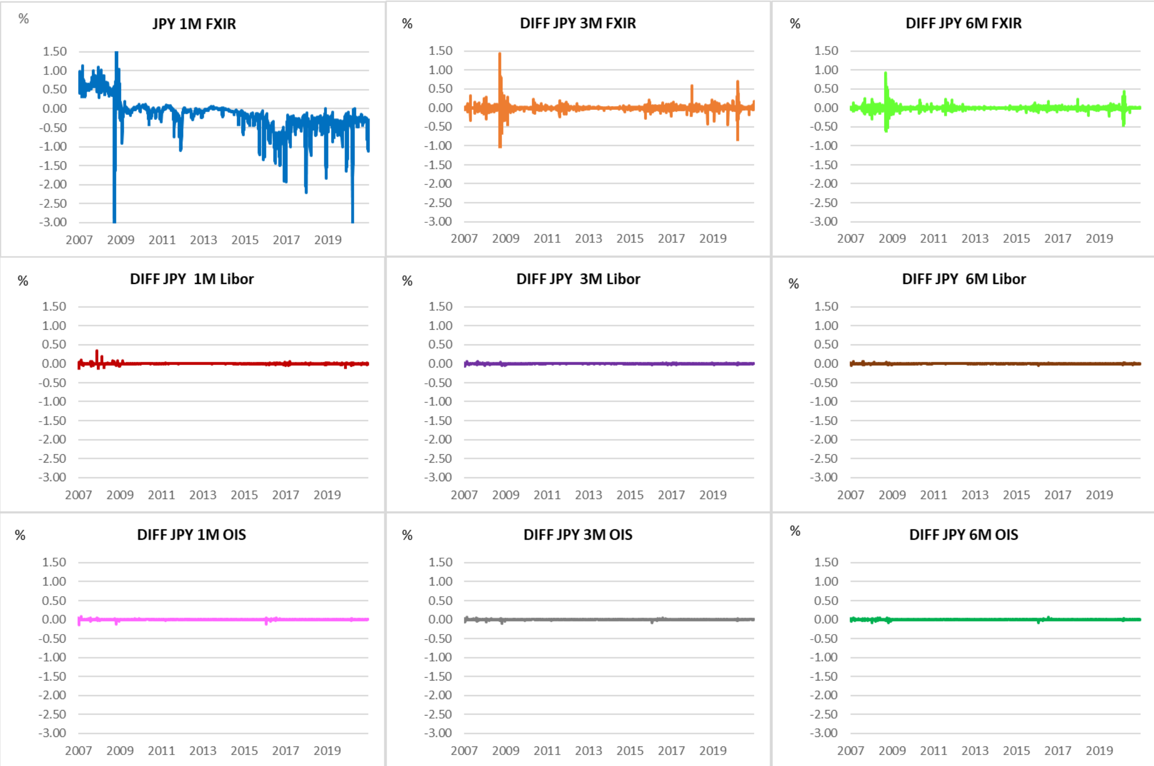
Table 5 Summary statistics: JPY interest rates, 2/1/2007 – 31/12/2020

	JPY 1M FXIR	JPY 3M FXIR	JPY 6M FXIR	JPY 1M LIBOR	JPY 3M LIBOR	JPY 6M LIBOR	JPY 1M OIS	JPY 3M OIS	JPY 6M OIS
Mean	-0.1617	-0.0302	0.1057	0.1456	0.2110	0.2986	0.0894	0.0881	0.0873
Variance	0.2287	0.1809	0.2010	0.0689	0.0951	0.1086	0.0303	0.0336	0.0382
Skewness	-1.068***	0.77***	0.90***	1.47***	1.34***	1.02***	1.58***	1.60***	1.62***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Ex.Kurtosis	8.14***	0.50***	0.06	1.42***	0.73***	-0.05	1.51***	1.65***	1.93***
	(0.0000)	(0.4350)	(0.0000)	(0.0000)	(0.5410)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
JB	10421.61***	388.45***	477.12***	1571.80***	1134.26***	605.91***	1810.82***	1900.08***	2096.25***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
ERS	-4.142***	-1.825*	-1.318	-0.713	0.311	0.446	-0.008	0.303	0.32
	(0.0000)	(0.0680)	(0.1890)	(0.4760)	(0.7560)	(0.6560)	(0.9930)	(0.7620)	(0.7490)
Q(10)	14097.725***	17921.263***	18745.034***	19191.043***	19352.090***	19360.718***	19275.158***	19273.883***	19250.426***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Q2(10)	3625.815***	14255.811***	17190.250***	18723.061***	19309.694***	19331.302***	19212.034***	19229.536***	19196.973***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)

Source: Bloomberg and author's calculations

Notes: * p < 0.1; ** p < 0.05; *** p < 0.01. ( ) denote standard errors. The D'Agostino (1970) and Anscombe and Glynn (1983) statistics are used for skewness and kurtosis. JB (Jarque and Bera 1980) is the test for Normality, ERS unit root test (Stock et al. 1996) tests for stationarity, Q(20) and Q2 (20) are the weighted Ljung-Box statistic for serial correlation in the returns and squared series (Fisher and Gallagher 2012), respectively

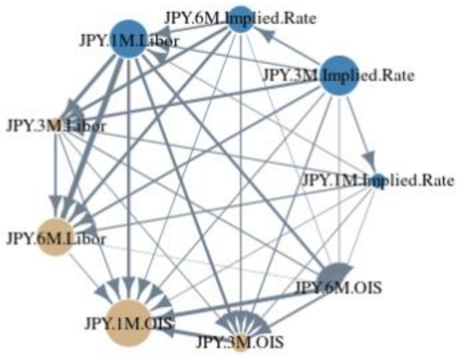
Figure 14 First differenced JPY Interest rates



4.3.1. Static Volatility Connectedness – JPY interest rates

The static analysis in Table 6 shows that the network of JPY rates is moderately connected. JPY interest rates recorded a TCI of 57.36 compared to the EUR interest rates (66.41) and GBP interest rates (70.25). Further, Figure 15 and the "TO" indicator in Table 6 below show that JPY FIXRs (55.95, 69.15, 64.10) and the JPY 1M LIBOR (65.45) have a high influence on the network of JPY interest rates. On a net basis, the "NET" indicator shows that JPY FXIRs and the JPY 1M LIBOR are net transmitters of shocks to the network. On the other hand, the "FROM" indicators show that the OIS and JPY 3M LIBOR and JPY 6M LIBOR rates have the highest effect from the shocks of others in the system. The "NET" measure shows that on a net basis the OIS rates and JPY LIBOR rates (3M and 6M) are net recipients of shock from the system.

Figure 15 Network of JPY Interest rates



Notes: Blue (yellow) nodes represent net transmitter (net recipient) of shocks. Vertices are weighted by averaged net pairwise directional connectedness measures. The size of nodes represents weighted average net total directional connectedness. The network plot results are based on a TVP-VAR model with lag length of order one (BIC) and a 10-step-ahead generalized forecast error variance decomposition.

Table 6 Average Dynamic Connectedness – JPY interest rates

	JPY 1M FXIR	JPY 1M FXIR	JPY 3M FXIR	JPY 1M LIBOR	JPY 3M LIBOR	JPY 6M LIBOR	JPY 1M OIS	JPY 3M OIS	JPY 6M OIS	FROM Others
JPY 1M FXIR	48.24	19.64	12.99	8.18	3.50	2.43	1.41	1.60	2.00	51.76
JPY 3M FXIR	18.50	41.53	20.71	5.39	3.95	3.01	1.76	2.37	2.76	58.47
JPY 6M FXIR	13.08	22.16	43.21	4.80	3.16	3.71	2.33	3.28	4.27	56.79
JPY 1M LIBOR	8.94	6.60	6.45	44.80	14.06	8.66	3.04	3.54	3.92	55.20
JPY 3M LIBOR	4.62	6.21	5.60	16.97	40.23	14.04	4.13	3.55	4.65	59.77
JPY 6M LIBOR	3.68	4.75	6.02	12.90	15.85	40.53	5.13	4.51	6.62	59.47
JPY 1M OIS	2.10	2.76	3.15	5.26	5.18	5.96	43.92	15.99	15.69	56.08
JPY 3M OIS	2.45	3.59	4.41	5.81	4.39	4.57	13.08	41.81	19.90	58.19
JPY 6M OIS	2.58	3.44	4.77	6.14	5.77	6.98	12.65	18.15	39.52	60.48
TO others	55.95	69.15	64.10	65.45	55.86	49.36	43.54	52.98	59.81	516.20
Inc. own	104.19	110.68	107.32	110.25	96.09	89.89	87.46	94.78	99.34	TCI
NET	4.19	10.68	7.32	10.25	-3.91	-10.11	-12.54	-5.22	-0.66	57.36
NPDC	1	0	2	3	4	5	8	7	6	

Notes: the results are based on TVP-VAR model with a lag length of order one (BIC) and a 10-step ahead generalised forecast variance decomposition

4.3.2. Total Dynamic Connectedness -JPY interest rates

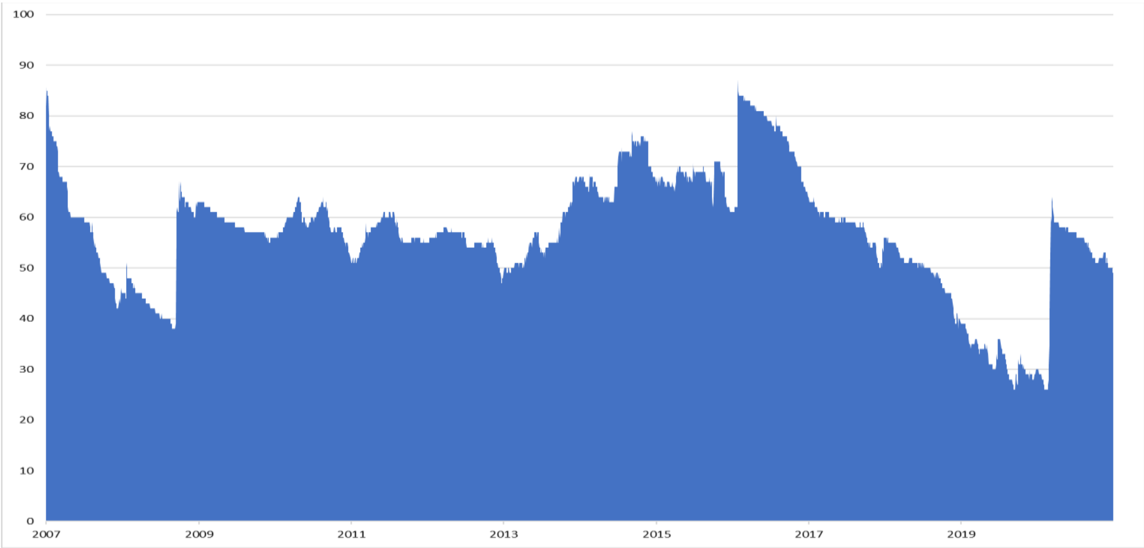
The evolution of the JPY interest rates as shown by the TCI (Figure 16) is above 60 most of the time, showing that the instruments are highly connected overtime. The TCI is time varying and has peaks which coincide with market events. As alluded by Chatziantoniou, Gabauer and Stenfors (2021). High interconnectedness arises to the fact that in a market stress market risk premia rises, and the central bank intervenes to reduce risk premia. Japan unlike other major economies was one of the first economies to adopt unconventional monetary policy that involved close to zero interest rates, forward guidance, and quantitative easing. This is because Japan was facing a crisis since the 1990s. Consequently, the monetary policy easing was already in force at the time of the crisis.

The TCI peaked at 64 on 7 October 2008 after the collapse of Lehman brothers on 15 September 2008. Bank of Japan's subsequent reduction of the target for uncollaterised overnight call rate from around 0.5% to 0.3% on 31 October 2008. The Bank of Japan further reduced this rate to around 0.1% on 19 December 2008. The TCI peaked at 98.71 on 8 January 2016, stayed above 90 up to 23 June 2016. It started declining but was above 80 up to end October 2016. The period of a high TCI from September 2016 onwards coincides with the introduction of the "framework for strengthening monetary easing" by Bank of Japan in September 2016. This involved the introduction of QQE and a yield curve control. Under this arrangement, the Bank of Japan committed to control the short-term and long-term rates. Further, Bank of Japan committed to expanding the monetary base until the inflation target was met (Bank of Japan, 2016).

Further, high interconnectedness is observed for the period March 2020. This coincides with the covid-19 crisis. As Bank of Japan (2020) state, in response to this crisis, Bank of Japan adopted and implemented three (3) measures. First, a special programme to support corporate financing through purchases of commercial paper and corporate bonds. Second, provision of JPY and foreign currency funds [10]. Third, the bank made purchases of electronic traded funds and J-REITS[11]

[10] Under Bank of Japan's yield curve control programme, purchases of unlimited Japanese Government Bonds were made as well as provision of USD funding.
[11] Corporate type closed funds listed on the stock exchange.

Figure 16 Total Dynamic Connectedness - JPY interest rates

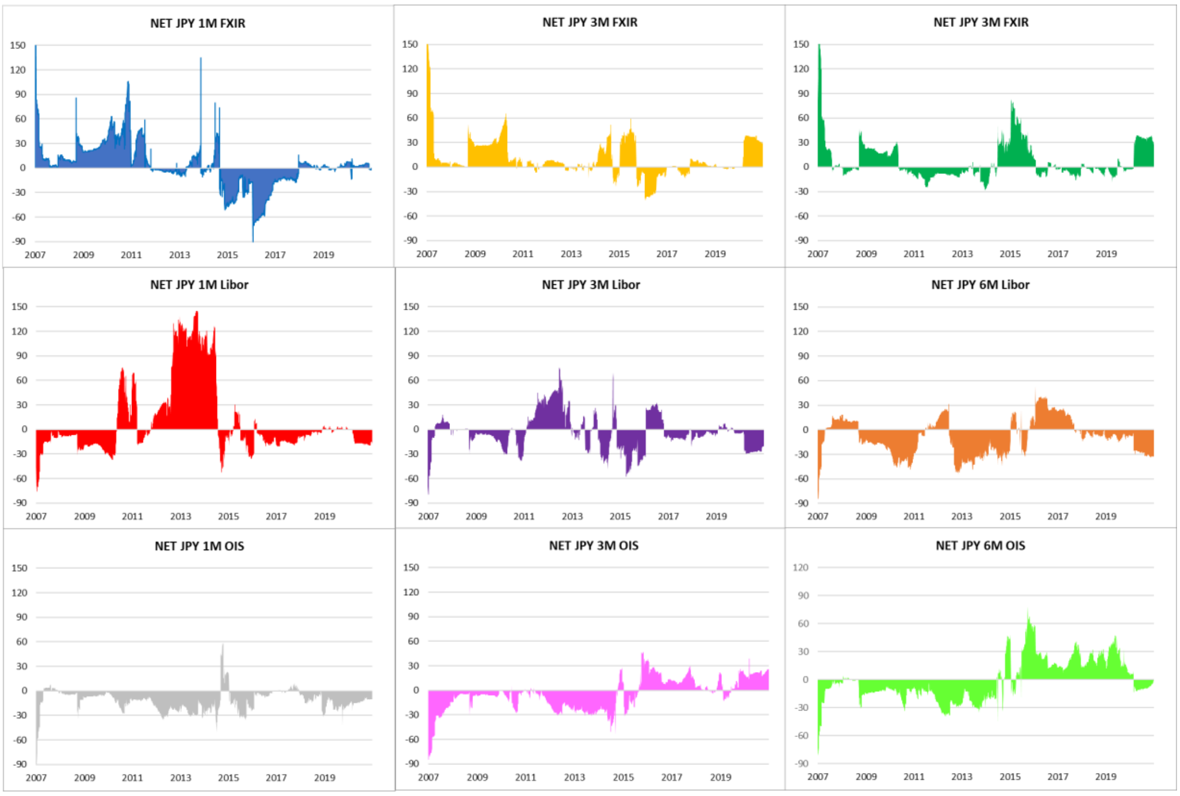


Notes: The Total Connectedness Index is based on a TVP-VAR model with a lag length of order one and a 10-step-ahead generalized forecast error variance decomposition based on the Bayesian Information Criterion (BIC).

4.3.3. Net Total Directional Connectedness – JPY interest rates

On a net basis, Figure 17 below shows that JPY FXIRs are net transmitters of shocks during the 2007-08 GFC and the Covid crisis in 2020. JPY LIBOR rates assumed a mixed role but were net recipients most of the time. On the other hand, the OIS (JPY 3M OIS and JPY 6M OIS) were net transmitters post-2014 while the short-term (1M JPY OIS) assumed the net receiving role most of the period. Figure 18 below provides the dynamics of the bi-directional relationships of variables. The bidirectional relationship (Net Pairwise Directional Connectedness) is presented in Figure 18.

Figure 17 Net Total Connectedness – JPY interest rates



Notes: The results are based on a TVP-VAR model with lag length of order one (BIC) and a 10-step-ahead generalized forecast error variance decomposition

4.3.4. Net Pairwise Dynamic Connectedness – JPY interest rates

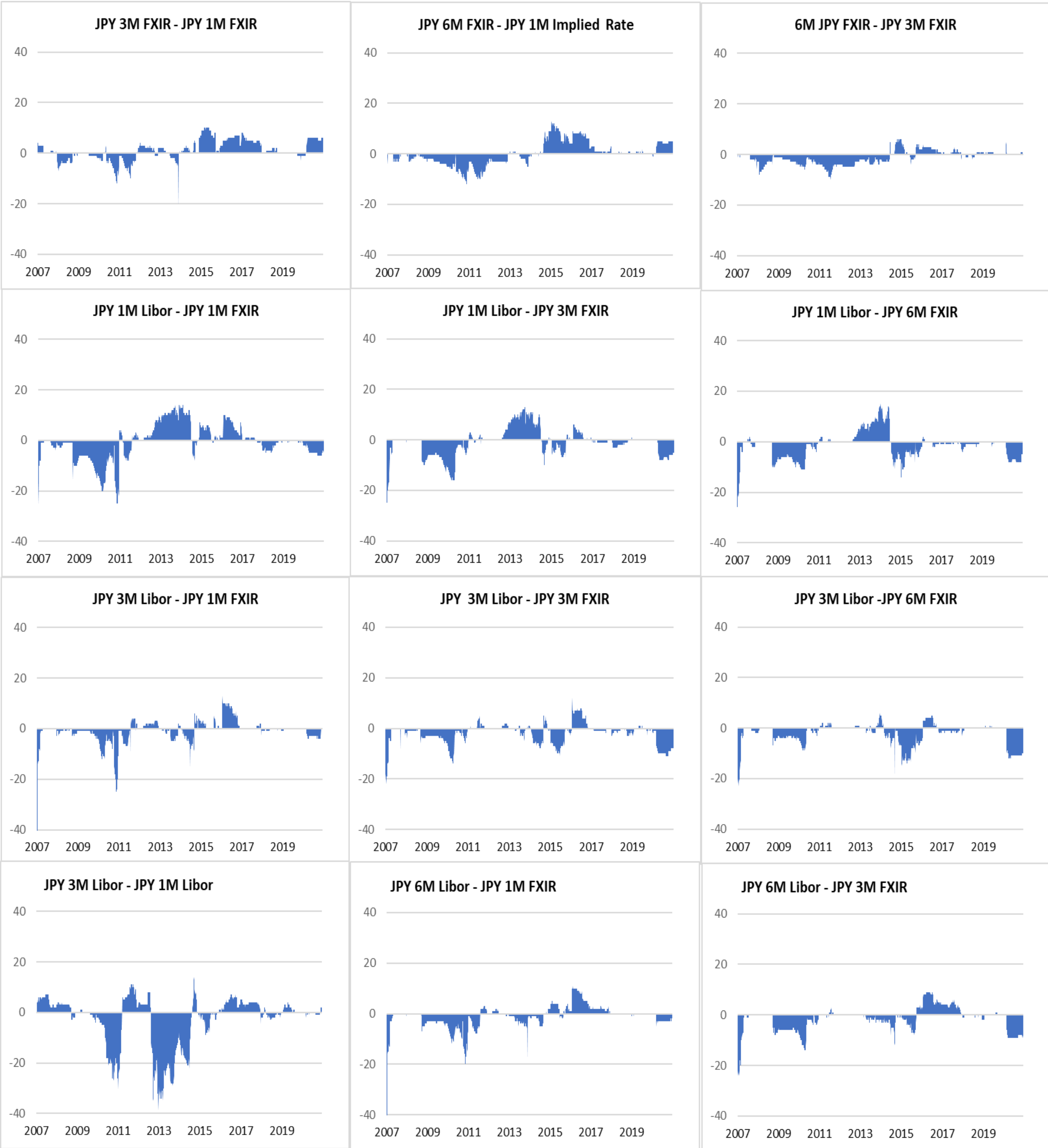
According to the MTM logic, shocks must be transmitted from the 1M to 3M, and 6M rates before being transmitted to the real rates (affecting household and firm decisions), and finally output, inflation, and employment. The short-term rates are the first stage of the interest rates channel of MTM.

While the 1M and 3M assume mixed roles overtime, contrary to the MTM logic, 3M OIS dominates the transmission of shocks to 1M OIS post-2007-08 GFC. This is an indication that expectations of nominal short-term money market rates are not related to long-term money market rates. As regards JPY LIBOR rates, the MTM logic is violated post-2014. This is the case for the JPY 6M LIBOR and JPY 3M LIBOR, and the JPY 3M and JPY 1M LIBOR. Similarly, the JPY 6M LIBOR dominates its influence on the JPY 1M LIBOR post-2015. Post-2016 the relationship between 1M, 3M, and 6M maturity categories could have been disconnected when the Bank of Japan introduced long-term yield curve control as part of the unconventional monetary policy measures. This is consistent with Stenfors (2022) viewpoint that the shift to long-term yields as the anchor for expectations by BOJ could have shifted the attention (market expectations) from short-term to long-term rates thereby impairing the first stage of MTM. On the other hand, the transmission of shocks from the 1M, 3M tenors to the 6M FXIRs varies over time. Strikingly, unlike LIBOR rates and OIS, the short-term part (1M, 3M) of the FXIRs yield curve dominates the transmission of shocks to the 6M JPY FXIR post 2014.

The OIS and JPY LIBOR rates assume mixed roles overtime, with the former dominating transmission after 2014. Further, there are some periods when the two markets were completely disconnected. The picture is the same as regards to the transmission of shocks between the OIS and FXIRs. This implies that the interbank money market did not react to market expectations of future short-term interest rates. The fact that these two market segments begin to react to market expectations of the future short-term rates post-2014 after the introduction of the QQE in April 2013 is perhaps an indication that markets were confident that these measures would help to meet the Bank of Japan objectives. According to Bank of Japan (2013 pp 1-2), the Bank of Japan expected the QQE to drastically change the market expectations in addition to other MTM channels such as longer-term interest rates and asset prices.

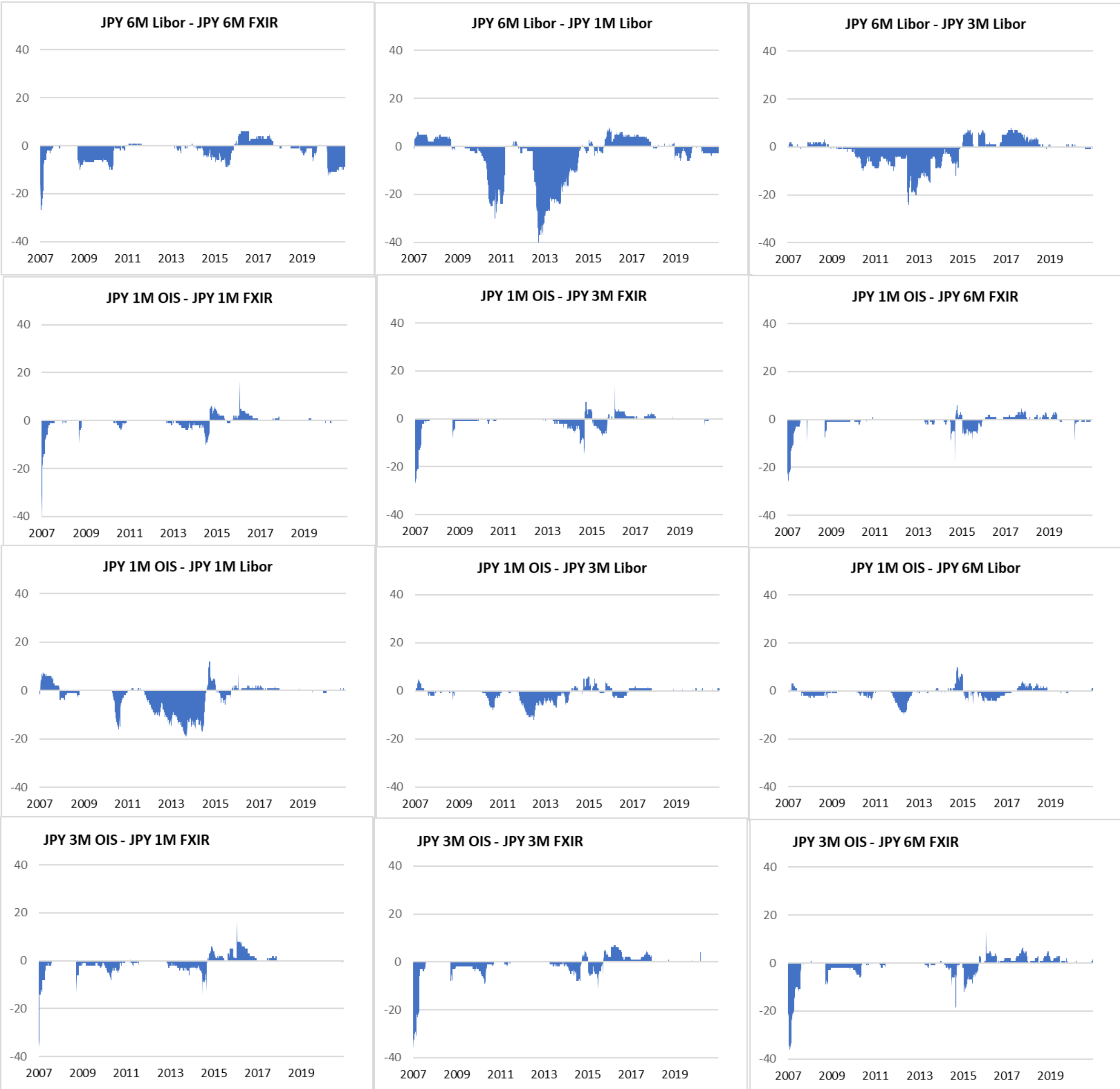
As regards to the bi-directional relationship between JPY FXIRs and JPY LIBOR rates, for the 1M maturity category, the former dominate transmission of shocks to the later during the 2007-08 GFC, and up to 2011, and during the covid-19 crisis. For the 3M and 6M maturity categories, there is a mixed role, with the FXIRs dominating transmission of shocks to the JPY FXIRs. As Shirakawa (2021) states, the foreign exchange swap market was facing challenges due to increased counterparty risks. The USD funding strains in the foreign exchange swap continued to present challenges in the JPY foreign exchange swap market. In response, there was an international coordination of swaps lines for the Federal Reserve to supply the USD to central banks including Bank of Japan (Shabani, Stenfors and Toporoski, 2021). Further, the Bank of Japan continued in its QQE continued with efforts to provide USD foreign currency funding.

Figure 18 Net Pairwise Dynamic Connectedness – JPY interest rates



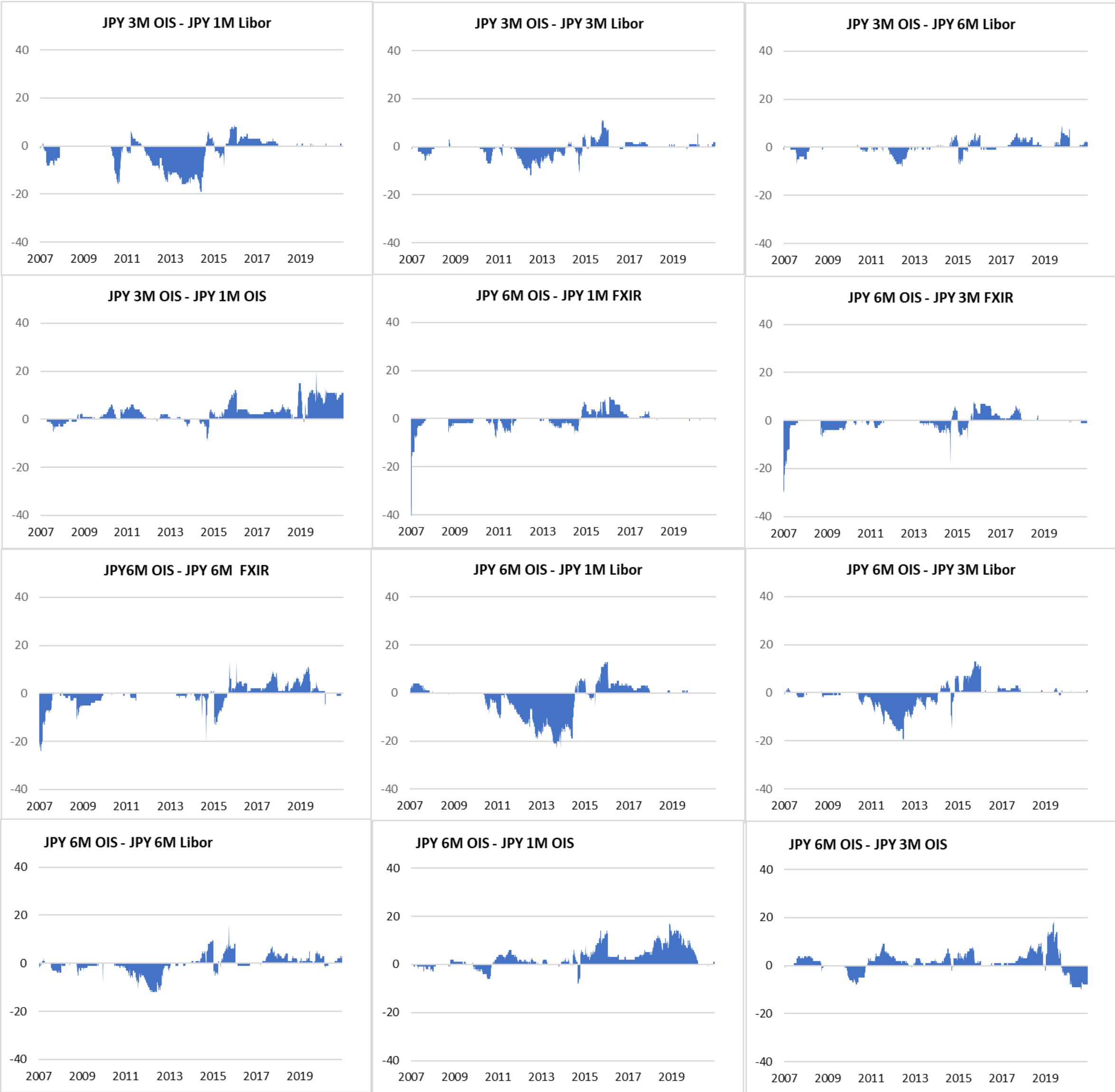
Notes: The results are based on a TVP-VAR model with lag length of order one (BIC) and a 10-step-ahead generalized forecast error variance decomposition

Figure 18 Net Pairwise Dynamic Connectedness – JPY interest rates



Notes: The results are based on a TVP-VAR model with lag length of order one (BIC) and a 10-step-ahead generalized forecast error variance decomposition

Figure 18 Net Pairwise Dynamic Connectedness – JPY interest rates



Notes: The results are based on a TVP-VAR model with lag length of order one (BIC) and a 10-step-ahead generalized forecast error variance decomposition.

5. Conclusion

This study empirically analyses the volatility connectedness of overnight index swaps, foreign exchange swaps (FXIRs), and LIBOR rates for 1M, 3M, and 6M maturity categories for the EUR, GBP, and JPY. The results show that GBP interest rates have the highest interconnectedness (70.25), followed by EUR interest rates (66.41) and JPY interest rates (57.26). Key conclusions are as follows: First, the connectedness of interest rates for all currencies is time-varying. Second, high connectedness coincides with international events and domestic institutional specificities and policies. Third, while there are some similarities across currencies, there are some variations in the transmission of shocks across variables.

As regards the MTM logic, that is, the transmission of shocks across the money market yield curve, the findings also vary per currency. Static indicators show that EURIBOR rates are net recipients of shocks in the system while OIS and FXIRs (except the 6M) are net transmitters of shocks in the system. Further, the TCI varies with time and high connectedness coincides with international events (e.g. USD funding liquidity) and euro area events including the Euro sovereign debt crisis, and the covid-19 crisis. Turning to the specifics regarding the bi-direction transmission of shocks across type of interest rates and maturity categories. The results show that the 1M OIS, 3M OIS, and 6M OIS maturity categories assume both transmitting and receiving roles in transmitting shocks in the system. While the 3M OIS dominates transmission of shocks to 6M OIS in line with the MTM logic, there seems to be a disconnect between the 1M OIS (central bank announcements) transmission of shocks to the 3M OIS and 6M OIS, as the former dominates transmission to the latter. In line with the MTM logic, the 1M and 3M EUR FXIR dominate transmission to the 6M EUR FXIR. Similar to the EUR OIS, there is a challenge in transmitting shocks from the 1M EUR FXIR to the 3M EUR FXIR. Similarly, EURIBOR maturity categories assume a mixed role of transmission of shocks over time. Specifically, while the 1M and 3M dominate transmission to the 6M maturity category is in line with the MTM logic, the transmission of shocks from the (1M) to the (3M) assumes a mixed role.

As regards the bidirectional the bi-directional relationships of instruments (FXIRs, OIS, and EURIBOR rates) over time, the analysis shows the transmission of shocks from OIS, an indication of market expectations to the unsecured market segment (EURIBOR) was in accordance with the MTM logic. The unsecured interbank market (EURIBOR) reacted to market expectations (OIS) most of the time. However, the relationship between FXIRs and OIS shows that the two instruments assume mixed roles, with the former not responding to market expectations during the 2007/2008 GFC and 2013 – 2015 in the respective 3M and 6M maturity categories. As regards the bi-directional relationship between FXIRs and EURIBOR rates, the two interest rates assumed mixed roles over time.

The static analysis shows that the OIS and GBP LIBOR rates (1M and 3M) are net transmitters of shocks to the system, while GBP FXIRs and the 6M GBP LIBOR are net recipients of shocks in the system. The MTM across maturity categories for OIS show that while all maturity categories assume mixed roles over time, the 3M dominates transmission to the 6M tenor. Similar to EUR interest rates, there seems to be a disconnect between the transmission of the central bank announcements (1M) to the 3M maturity category. Further, the 1M and 6M maturity assume mixed roles in the transmission of shocks.

As regards GBP FXIRs, there is a mixed role in the transmission across the short-term, medium-term, and long-term parts of the money market yield curve. Specifically, in line with the MTM logic, the central bank announcements dominate transmission to the 3M and 6M categories prior to 2014. However, this relationship is disconnected post-2014, as the 3M and 6M dominate their influence on 1M. Similarly, the 3M maturity category dominates its influence on the 6M prior to 2014 but the direction of shocks changes post-2014. As regards the GBP LIBOR rates, it seems the maturity categories assume mixed roles in transmitting shocks in the system. In line with the MTM logic, the 1M dominates its influence on the 3M tenor and the 6M maturity category. Additionally, the 3M maturity category dominates transmission to the 6M tenor.

Turning to the bi-directional relationship between the OIS (market expectations) and GBP LIBOR rates and GBP FXIRs. Starting with the bi-directional relationship between the OIS and GBP LIBOR rates. The OIS dominate the transmission of shocks to the GBP LIBOR rates, except for the period 2011-2014. As regards to the relationship between OIS and FXIRs, while the 3M OIS dominates transmission to the 3M GBP FIXRs, the 1M OIS and 1M GBP FXIRs, 6M OIS and 6M GBP FXIRs assume mixed roles overtime in terms of transmission of shocks. Turning to the relationship between FXIRs and GBP LIBOR rates, it is noted that the foreign exchange swap market (FXIRs) dominates its influence on the unsecured market segment (GBP LIBOR rates) during the 2007-08 GFC, the latter dominates transmission to the former post-2011.

For the JPY interest rates, the static analysis shows that JPY FXIRs and the JPY 1M LIBOR are net transmitters of shocks to the network. On the other hand, the OIS rates and JPY LIBOR rates (3M and 6M) are net recipients of shock from the system. Turning to the bi-directional relationship, like the EUR interest rates, while the 1M and 3M assume mixed roles overtime, contrary to the MTM logic, 3M OIS dominates the transmission of shocks to 1M OIS post-2007-08 GFC. This is an indication that expectations of nominal short-term money market rates are not related to long-term money market rates. As regards JPY LIBOR rates, the MTM logic is violated post-2014. This is the case for the JPY 6M LIBOR and JPY 3M LIBOR, and the JPY 3M and JPY 1M LIBOR. Similarly, the JPY 6M LIBOR dominates its influence on the JPY 1M LIBOR post-2015. On the other hand, the transmission of shocks from the 1M, 3M tenors to the 6M FXIRs varies over time. Strikingly, unlike LIBOR rates and OIS, the short-term part (1M, 3M) of the FXIRs yield curve dominates the transmission of shocks to the 6M JPY FXIR post 2014.

The OIS and JPY LIBOR rates assume mixed roles overtime, with the former dominating transmission after 2014. Further, there are some periods when the two markets were completely disconnected. The picture is the same as regards to the transmission of shocks between the OIS and FXIRs. This implies that the interbank money market did not react to market expectations of future short-term interest rates. As regards to the bi-directional relationship between JPY FXIRs and JPY LIBOR rates, for the 1M maturity category, the former dominate transmission of shocks to the later during the 2007-08 GFC, and up to 2011, and during the covid-19 crisis. For the 3M and 6M maturity categories, there is a mixed role, with the FXIRs dominating transmission of shocks to the JPY FXIRs.

These results have policy implications. First, reflecting on the regulators' paradigm shift from estimation-based to alternative rates that are more robust or less volatile, there is no 'one fits it all' model as to which interest rates make a better alternative. This implies that jurisdictions need to understand the specific behaviour (in both crisis and calm periods) before selecting a benchmark. Second, the effectiveness of monetary policy varies across currencies and remains vulnerable to domestic and institutional specificities.

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