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The global economic policy uncertainty spillover analysis: In the background of COVID-19 pandemic

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\textbf{ABSTRACT}

Combining the spillover index approach and LASSO-VAR method, we construct the spillover network of 19 specific countries’ economic policy uncertainty (EPU). Then we deconstruct the constructed network into four blocks by the block models, the impacts of COVID-19 on EPU spillover effects between each country and blocks is analyzed gradually. The results reveal that: (1) The transnational contagion of EPU is significant, and the spillover network of policy uncertainty is time-varying. (2) EPU networks can be divided into four different blocks by block models. The role of blocks and the spatial spillover transmission path between blocks are different in different periods. (3) The new infection cases and deaths of COVID-19 have a significant effect on reception and transmission directional EPU spillovers, while there is no significant impact on net spillovers. The international movement restrictions during the period of COVID-19 significantly increase the directional and net EPU spillovers. Our findings have some implications for policy-makers and market regulators in the context of the COVID-19 pandemic.

1. Introduction

In recent years, the problem of global uncertainty has become increasingly prominent. E.g., the lack of momentum of world economic growth, the emergence of regional hot issues, especially the outbreak of COVID-19 epidemic which looks as a special case of a dual health and economic crisis (Atri et al., 2021), etc., which poses great threat to global economic and social stability. As a specific form of uncertainty, economic policy uncertainty will have a significant impact on the global micro-economy and macro-economy (Goodell et al., 2020b, 2021).\textsuperscript{1} Moreover, due to the close relationship between countries in international trade and financial markets, the economic policy uncertainty among countries forms a complex transmission network (Marfatia et al., 2020), meaning that increasing economic policy uncertainty is not only a problem faced by a country (or region), but also a common problem faced by global economies in the context of COVID-19 pandemic (Goodell, 2020a). Thus, as the COVID-19 pandemic continues to evolve, its impact on the global economy has not yet been fully revealed, identifying the transactional spillover effects and paths of global

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\textsuperscript{1} Considering the causes of EPU, we agree with Gulen and Ion (2016). i.e., “Since the 2007–2008 global financial crisis and the following Great Recession, governments worldwide have introduced fiscal, monetary, trade, and other types of economic policies to recover the economy. With the frequent adjustment of policies, economic subjects are challenging to make accurate judgments on the government’s behavior and cannot correctly predict the government’s instructions on the adjustment of current economic policies. As a result, EPU gradually arises.”
economic policy uncertainty play a crucial role in maintaining the smooth operation of the economy.

In the past few years, several "black swan" events have emerged, causing a renewed interest in studying the impacts of the economic policy uncertainty (EPU)\(^2\) index on macro and micro levels (Bloom, 2009; Pastor and Veronesi, 2012). E.g., stock markets (E.g., Li et al., 2015; Christou et al., 2017; Fang et al., 2018; Wang et al., 2020; Ashraf, 2020; Baek et al., 2020); cryptocurrency market (E.g., Wang et al., 2019; Wu et al., 2019; Aharon et al., 2022; Mokni et al., 2022); corporate behavior (E.g., Kim and Kung, 2016; Van Vo and Le, 2017; Bhattacharya et al., 2017; Kim and Yasuda, 2021), and risk management (E.g., Bernal et al., 2016; Al-Thaqeb and Algharabali, 2019; Li et al., 2021; Wu et al., 2021b). Within this fast-expanding literature, a set of papers have examined the spillover effect of EPU (E.g., Klööner and Sekkel, 2014; Antonakakis et al., 2018; Gabauer and Gupta, 2018; Bhattarai et al., 2019; Tang et al., 2021; Nong, 2021), and the results show that the "black swan" events strengthen the spillover effect. However, the impact of the COVID-19 epidemic on EPU spillover is relatively poorly studied. Few literatures suggest that the COVID-19 pandemic affects the spillover and connectedness between EPU and other financial markets (Li et al., 2021; Dou et al., 2022), while the results are limited to the comparisons between different periods. Whether the severity of COVID-19 crisis will affect EPU spillover which is essential to expand research about the consequences of the financial market health crisis has not been discussed.

Accordingly, based on the realistic background and academic research needs, it is necessary to investigate the spillover effects among countries’ EPU, also, we aim to focus on the dynamic characteristics of EPU spillover network and the impact of COVID-19 on these spillover effects. Moreover, there are several important issues to be clarified, e.g., are the dynamics of EPU in one country influenced by uncertainty shocks in other countries? What is the structure of the transmission network of global EPU? What are the spillover channels between different blocks? Are the spillover effects greater in countries with more severe COVID-19 pandemic? In this context, solving these problems can provide important references for regulators to prevent external shocks effectively, also help governments to enhance the pertinence and predictability of macro-control.

To answer these questions, we combine the Diebold and Yilmaz (2012) spillover measures and the 19 countries’ monthly EPU indices from January 1997 to January 2021 of Baker et al. (2016), to build the spillover network of global EPU. The spillover network is estimated by the LASSO methods, which facilitates high dimensionality by selecting and shrinking in optimal ways (Demirer et al., 2017), in the Diebold and Yilmaz (2012) framework. Furthermore, we innovatively assess the roles of different spillover blocks using block models, and analyze the transmission paths of EPU spillover in different blocks. Finally, this study provides evidence of the COVID-19 new confirmed cases and deaths numbers’ effects, and the COVID-19 measures on spillovers during the global health crisis.

Regarding the discussion, we find that there is significant and time-varying transnational contagion effect among each country’s EPU, and the global major event shocks play some impact on these effects. After deconstructing the constructed spillover network, we also show which countries are transmitting uncertainty shocks and receiving it most. Moreover, the result of block model reveals that the EPU network can be divided into four different spillover blocks, and we define the roles of different blocks in different periods through this results, which will reflect spillover path more clearly. Last but not the least, the new infection cases and deaths have a significant U-curve effect on reception and transmission directional EPU spillovers, while there are no significant impacts on net spillovers, and the international movement restrictions significantly increase the directional and net EPU spillovers. These results will help us to understand both of how COVID-19 is impacting economic and financial policies and how do EPU influence each other during extreme, global, pandemic.

The contribution of our research is empirical rather than methodological, there are three main points. Firstly, we use variance decomposition and LASSO-VAR model to analyze the spillover and connectedness of different countries’ EPU at different levels. The dynamic characteristics of spillover effect in time dimension and path structure in spatial dimension are comprehensively captured from the perspective of connected network. Secondly, we assess the roles of different spillover blocks using block models, and explore the transmission mechanism of EPU spillover in different blocks, which reveals the spillover path of EPU between blocks more clearly. Thirdly, we analyzed the impact of the severity and measures of the "black swan" event on spillovers using the number of new confirmed cases and deaths, as far as we know, few studies have applied these elements to quantitative economic analysis; also, according to the research results, we put forward some policy implications.

The remainder of the paper is organized as follows. Section 2 presents the relevant literature review. Section 3 describe the dataset and methodology for calculating spillovers, "LASSOed" large VARs as empirical approximating models and block models. Section 4 includes a discussion of the empirical results. Section 5 concludes the study and puts forward the policy implications.

2. Literature review

EPU is an unpredictable risk arising from the process of policy adjustment. The effective measurement of EPU is essential to the related theoretical and empirical research. At present, there are two main methods to measure the EPU. One is measured by non-economic dummy variables (E.g., Julio and Yook, 2012) or the volatility of a single economic policy variable (E.g., Creal and Wu, 2016). However, the main problem of this method is that many policy changes are difficult to be modeled through standard statistics. The other method constructs a synthetic index based on text analysis (E.g., Baker et al., 2016; Manela and Moreira, 2017; Huang et al., 2016). This comprehensive index can reflect the overall level of EPU, with good continuity, traceability and time variability. Therefore,

\(^2\) Note that in this paper the term “EPU” denotes economic policy uncertainty, and the “EPU index” refers to the economic policy uncertainty index developed by Baker et al. (2016).

\(^3\) Which represent the severity of COVID-19 and school closing, workplace closing and international movement restrictions to represent the measures.
Table 1: Studies that related with EPU spillovers.

| Reference            | Methodology | Variable            | Country                                      | Frequency | Period       | Key findings                                                                 |
|----------------------|-------------|---------------------|----------------------------------------------|-----------|--------------|-----------------------------------------------------------------------------|
| Klošner and Sekkel   | DY          | EPU                 | Canada, France, Germany, Italy, UK, and US   | monthly   | 1997.1–2013.9 | The US and UK are responsible for a large fraction of the spillovers       |
| Balli et al. (2017)  | DY          | EPU                 | Australia, Brazil, Canada, Chile, China, France, Germany, Italy, Ireland, Japan, Korea, New Zealand, Russia, Sweden, UK, and US | monthly   | 1998.1–2015.12 | Bilateral factors play a highly significant role in explaining the magnitude of EPU spillovers |
| Antonakakis et al.   | TVP-VAR     | connectedness       | Canada, Japan, EU, UK, and US               | daily     | 2003.5–2017.10.2 | A significant uncertainty transmission from the EU to the US                |
| Bai et al. (2019)    | BK          | EPU                 | China, France, Germany, Japan, UK, and US   | monthly   | 2000.1–2019.3 | US seems to be both the major risk spillover contributor and receiver       |
| Cui and Zou (2020)   | BK          | EPU                 | Australia, Brazil, Canada, China, France, Germany, India, Italy, Japan, Mexico, Russia, South Korea, UK, and US | monthly   | 2003.1–2019.1 | The connectedness among EPU is significant                                 |
| Cekin et al. (2020)  | Vine copula | EPU                 | Brazil, Chile, Colombia, and Mexico        | monthly   | 1996.1–2018.5 | The contagion of uncertainty was significant before 2008 but became less important after 2008 |
| Marfatia et al. (2020) | DCC-GARCH, MST | EPU | Australia, Brazil, Canada, Chile, China, France, Germany, Italy, Ireland, Japan, Korea, Mexico, Russia, Sweden, UK, and US | monthly   | 1998.1–2018.5 | The nature and dominance of the EPU network have changed significantly over time. |
| Li et al. (2021)     | MST         | EPU                 | Australia, Canada, Chile, China, Hong Kong, India, Indonesia, Japan, Korea, Malaysia, Mexico, Russia, Singapore, Taiwan, Thailand, Vietnam, and US | daily     | 2017.1–2020.6.30 | China is the Asia-Pacific EPU network’s center                             |
| Osei et al. (2021)   | Threshold cointegration | EPU | China, India, Japan, and South Korea | monthly   | 1997.1–2020.4 | The adjustments towards the long-run equilibrium position are asymmetric |
| Abakah et al. (2021) | Fractional cointegration | EPU | Canada, France, Ireland, Japan, Sweden and US | monthly   | 1985.1–2019.10 | There is very little evidence of crosscountry linkages of EPU              |
| Gabauer and Gupta (2018) | TVP-VAR connectedness | FPU, MPU, TPU, and CPU | Japan and US                                   | monthly   | 1987.1–2017.12 | MPU is the main driver, followed by FPU, CPU and TPU                      |
| Antonakakis (2019)   | TVP-VAR connectedness | EPU, MPU, CPU, and Banking, Tax, Debt, Pension Policy Uncertainty | European and Greek | monthly | 1998.1–2018.3 | Greek EPU is dominating the European EPU                                   |
| Ma et al. (2019)     | DY          | EPU, MPU, FPU       | Argentina, Brazil, Canada, Chile, China, India, Indonesia, Japan, Korea, Malaysia, Mexico, Norway, Sweden, South Africa, Turkey, Euro, UK, and US | monthly   | 2000.1–2019.5 | Cross-category spillovers are countercyclical                               |
| Trung (2019)         | Global VAR  | EPU, MPU, and FPU   | Argentina, Brazil, Canada, Chile, China, India, Indonesia, Japan, Korea, Malaysia, Mexico, Norway, Sweden, South Africa, Turkey, Euro, UK, and US | monthly   | 2000.1–2013.12 | US policy uncertainty shocks are significant in driving the business cycle fluctuations of the world economy |
| Jiang et al. (2019)  | TVP-VAR connectedness | EPU, TPU, MPU, and FPU | China and US                                   | monthly   | 2000.1–2019.12 | Some major events may reverse the spillovers direction                     |
| Nong (2021)          | DY          | FPU, MPU, and TPU   | China and US                                   | monthly   | 2000.1–2019.12 | The direction of spillover is from the US to China                           |
| Tang et al. (2021)   | FAVAR, DY   | EU and EPU          | Australia, Canada, China, Japan, Malaysia, Mexico, Philippines, Russia, | monthly   | 2000.1–2020.3 | The contagion effects of EPU in the Asia-Pacific                          |

(continued on next page)
we use EPU index proposed by Baker et al. (2016) which is the most famous indicator to quantify the EPU to analyze the spillover effects of EPU.

With the increase of international dependence and the frequent occurrence of global problems, a growing number of scholars highlighted the spillovers of EPU and supported the existence of spillovers. There are mainly two streams of literature: the spillover effects of EPU on other financial markets or economic variables (Antonakakis et al., 2014; Dakhlaoui and Aloui, 2016; Kido, 2016; Liow et al., 2018; He et al., 2019; Yang, 2019; Wang et al., 2019, 2020; Xia et al., 2020; Ghirelli et al., 2021; Zhu et al., 2021; Dou et al., 2022), the cross-section or cross-category spillovers and spatial network of EPU (Klööner and Sekkel, 2014; Balili et al., 2017; Antonakakis et al., 2018, 2019; Gabauer and Gupta, 2018; Bai et al., 2019; Ma et al., 2019; Trung, 2019; Jiang et al., 2019; Cui and Zou, 2020; Cekin et al., 2020; Marfatia et al., 2020; Abakah et al., 2021; Li et al., 2021; Nong, 2021; Osei et al., 2021; Tang et al., 2021). We display the methodologies, countries, variables, frequencies, periods and key findings of these literatures in Table 1.

From Table 1 we note that most early literature focuses on the transnational spillover effects of EPU between developed countries, but lacks the analysis on developing countries. With the improvement of international status in developing countries and the increase of international cooperation, more and more literature began to study the spillovers of EPU across developed and emerging countries.

Table 1 (continued)

| Reference | Methodology | Variable | Country | Frequency | Period | Key findings |
|-----------|-------------|----------|---------|-----------|--------|--------------|
| Dakhlaoui and Aloui (2016) | GARCH | EPU and Stock markets | Singapore, South Korea, Thailand, and US Brazil, China, India, Russia, and US | daily | 1997.7-2011.7.27 | There is strong evidence of a time-varying correlation between US EPU and stock market volatility |
| Wang et al. (2020) | The framework of Barunik and Kehlík (2018) | EPU and Stock markets | China and US | monthly | 2000.1-2019.3 | EPU has a bigger effect on bad volatility in the stock market |
| He et al. (2019) | The framework of Barunik and Kehlík (2018) | EPU and Stock markets | Australia, Canada, China, Japan, UK, and US | monthly | 2000.1-2019.12 | S&P500 index volatility is a net recipient of spillovers from important EPU indexes |
| Liow et al. (2018) | DY | EPU and Stock, Real estate, Bond, Currency markets | Canada, China, France, Germany, Japan, UK, and US | monthly | 1997.2-2015.8 | Policy uncertainty spillovers lead financial market stress spillovers |
| Xia et al. (2020) | BK | EPU and Stock, Housing markets | China | monthly | 2005.7-2017.12 | The long-term information from the EPU and stock market affect the real estate markets |
| Ghirelli et al. (2021) | Quarterly VAR | EPU, GDP, Exports, and FDI | Argentina, Brazil, Chile, Colombia, Mexico, Peru, and Venezuela | monthly | 1997.1-2018.6 | Shocks in LA EPU dampen commercial relationships between Spain and LA countries |
| Wang et al. (2019) | Multivariate quantile, Granger causality risk test, Equity market uncertainty | EPU, VIX, and Bitcoin | US | daily | 2010.7.19-2018.5.31 | The inexistence risk spillover effect from EPU to Bitcoin |
| Kido (2016) | DCC-GARCH | EPU and REER | Australia, Brazil, Japan, Korea, Mexico, Euro, and US | monthly | 2000.1-2014.12 | US EPU and the returns of the high-yielding currencies are consistently negative |
| Dou et al. (2022) | Quantile Granger test, Quantile regression | EPU and Carbon market | Euro and US | daily | 2013.1.22-2021.7.2 | The COVID-19 pandemic affects the spillover and connectedness between EPU and carbon futures price return |
| Antonakakis et al. (2014) | Structural VAR, DY | EPU and Oil prices | Canada, China, France, Germany, India, Italy, Spain, Euro, UK, and US | monthly | 1997.1-2013.6 | EPU responds negatively to aggregate demand oil price shocks |
| Yang (2019) | DY | EPU and Oil prices | France, Germany, Italy, Japan, UK, and US | monthly | 1998.1-2017.12 | Crude oil prices behave like receivers of information from EPU |
| Zhu et al. (2021) | Wavelet-based VAR, DY | EPU, oil price, and commodity markets | China | monthly | 2004.8-2020.4 | The net connectedness of EPU and WTI in the system is positive |

Notes: DY model is based on the generalized variance decomposition proposed by Diebold and Yilmaz (2019); BK model is the time-frequency spillover framework proposed by Barunik and Kehlík (2018); TVP-VAR connectedness approach extends the approach of Diebold and Yilmaz (2009, 2012) by allowing the variances to vary via a stochastic volatility Kalman Filter estimation with forgetting factors proposed by Antonakakis and Gabauer (2017). TPU=Trade Policy Uncertainty; MPU=Monetary Policy Uncertainty; FPU=Fiscal Policy Uncertainty; CPU=Currency Policy Uncertainty.
However, most of them focus on the dynamic connectedness of EPU (e.g., Klößner and Sekkel, 2014; Antonakakis et al., 2018; Gabauer and Gupta, 2018; Antonakakis et al., 2019; Tang et al., 2021; Nong, 2021). The determinants of cross-country policy uncertainty spillovers are also further investigated, showing that bilateral trade, exchange rate, and investor sentiment play a highly significant role in explaining the magnitude of EPU spillovers (Balli et al., 2017; Jiang et al., 2019). However, the analysis of how COVID-19 epidemic affects the spillovers of EPU has not been fully evidenced. While the EPU spillovers may have changed in different periods with the time-varying nature of EPU. For example, the outbreak of the COVID-19 has caused significant fluctuations in EPU (Baker et al., 2020). Matuka (2020) indicate that new infection cases of COVID-19 epidemic in the US have a significant effect on the US EPU. Li et al. (2021) show that the COVID-19 outbreak has increased the density of network between the EPU and financial markets.

However, the samples of existing literature contain a relatively short period of the COVID-19 due to the time of the outbreak. However, the impact of COVID-19 on EPU may change with the outbreak and rebound of the global epidemic, so we apply 19 countries’ EPU to study the influence of COVID-19 on the dynamic EPU spillovers.

Besides, we also note that many academic investigations use the spillover index model proposed by Diebold and Yilmaz (2009, 2012, 2014), a novel extension of the TVP-VAR connectedness approach of Antonakakis and Gabauer (2017), global VAR method (Trung, 2019), GARCH models (Dakhlaoui and Aloui, 2016), vine copula method (Cekin et al., 2020), the minimal spanning tree (MST) (Marfatia et al., 2020; Li et al., 2021) and the method of Barunik and Kehlík (2018) to discuss the network of EPU in different domains. While they focus more on the network topology and the identification of important country nodes in the EPU network, but ignore the propagation mechanism analysis. Importantly, it is necessary to clarify how economic policy risk transfers across countries. Hence, we further use the block model to explore the economic policy risk spatial propagation path.

3. Methodology and data

3.1. Spillover measures

Diebold and Yilmaz (2012) introduce the total and directional spillover measures based on forecast error variance decompositions from the generalized vector autoregressive framework, in which forecast-error variance decompositions are invariant to variable ordering. We follow Diebold and Yilmaz (2012), considering a covariance stationary N-variable VAR(p):

\[
X_t = \sum_{i=1}^{\infty} \Phi_i X_{t-i} + \epsilon_t
\]

Where \(X_t\) is a vector of size \(N\), containing all EPU, and \(\epsilon \sim (0, \Sigma)\) is the vector of independently and identically distributed disturbances. The moving average representation is \(X_t = \sum_{i=0}^{\infty} A_i \epsilon_{t-i}\), where, \(A_i \) is the \(N \times N\) coefficient matrices, which obey the recursion \(A_i = \Phi_1 A_{i-1} + \Phi_2 A_{i-2} + \cdots + \Phi_p A_{i-p}\), with \(A_0\) being the identity matrix and \(A_1 = 0\) for \(i < 0\).

Identification becomes challenging in high-dimensional situations that will concern us. Standard approaches such as Cholesky factorization depend on the ordering of the variables, which raises significant complications. Hence we follow Diebold and Yilmaz (2012) in using the generalized VAR framework, which produces variance decompositions invariant to ordering. Denoting the H-step-ahead forecast error variance decompositions by \(\theta^i_H\), for \(H = 1, 2, \ldots\), we have

\[
\theta^i_H = \sigma^2 \sum_{h=0}^{1} \left( \sum_{j=0}^{H} \left( \epsilon^i_{A_h} \sum_{k=j}^{H} \epsilon^i_{A_k} \right)^2 \right)
\]

Where \(\Sigma\) is the variance matrix for the error vector \(\epsilon\), \(\sigma^2\) is the standard deviation of the error term for the \(i\)th equation and \(\epsilon_i\) is the selection vector with one as the \(i\)th element and zeros otherwise. Because we work in the generalized VAR framework, the sum of the elements of each row of the variance decomposition is not equal to 1: \(\sum_{j=1}^{H} \theta^i_H \neq 1\). In order to use the information available in the variance decomposition matrix in the calculation of the spillover index, we normalize each entry of the variance decomposition matrix by the row sum as:

\[
\tilde{\theta}^i_H = \frac{\theta^i_H}{\sum_{j=1}^{H} \theta^i_H}
\]

Note that, by construction, \(\sum_{j=1}^{H} \tilde{\theta}^i_H = 1\) and \(\sum_{i=1}^{N} \tilde{\theta}^i_H = N\).

Following Diebold and Yilmaz (2012) several indexes are computed. The total spillover index measures the contribution of spillovers on the system’s forecast error variance.

\[
\sum_{i=1}^{N} \tilde{\theta}^i_H
\]

\[
S^i(H) = \frac{\sum_{i=1}^{N} \tilde{\theta}^i_H}{N} \times 100
\]

Next, directional spillovers are estimated. Within this type of spillovers, both transmission directional and reception directional spillover indexes are calculated for each market. The former contains the spillover contributions caused by market \(i\) on the rest of the
system, while the latter incorporates the summation of other markets spillovers on market \( i \). The transmission directional spillover index is defined as

\[
S'_T(H) = \frac{\sum_{j=1}^{N} \bar{g}_{ij}(H)}{N} \times 100
\]

And the reception directional spillover index is

\[
S'_R(H) = \frac{\sum_{j=1}^{N} \bar{g}_{ji}(H)}{N} \times 100
\]

After computing these two directional indexes, a net spillover index can be computed straight-forward as the difference between the transmission and reception spillover indexes

\[
S'_N(H) = S'_T(H) - S'_R(H)
\]

### 3.2. Estimation of high-dimensional VARs

In applications, we base spillover assessment on an estimated VAR approximating model. So, we need the VAR to be estimable in high dimensions, somehow recovering degrees of freedom. One can do so by pure shrinkage or pure selection, but blending shrinkage and selection, using variants of the LASSO (short for "least absolute shrinkage and selection operator"), proves particularly appealing.

To understand the LASSO, consider least-squares estimation:

\[
\hat{\Phi} = \arg \min_{\Phi} \sum_{t=1}^{T} \left( X_t - \sum_{i=1}^{p} \Phi_i X_{t-1} \right)^2
\]

Subject to the constraint: \( \sum_{i=1}^{q} |\Phi_i|^q \leq c \).

Equivalently, consider the penalized estimation problem:

\[
\hat{\Phi} = \arg \min_{\Phi} \left[ \sum_{t=1}^{T} \left( X_t - \sum_{i=1}^{p} \Phi_i X_{t-1} \right)^2 + \lambda \sum_{i=1}^{p} |\Phi_i|^q \right]
\]

Concave penalty functions non-differentiable at the origin produce selection, whereas smooth convex penalties produce shrinkage. Hence penalized estimation nests and can blend selection and shrinkage. The LASSO model, which was first introduced in the work of Tibshirani (1996), solves the penalized regression problem with \( q = 1 \), hence it shrinks and selects. Moreover, it requires only one minimization, and it uses the smallest \( q \) for which the minimization problem is convex.

A simple extension of the LASSO, the so-called adaptive elastic net (Zou and Zhang, 2009), not only shrinks and selects, but also has the oracle property, meaning (roughly) that the selected model is consistent for the best Kullback-Liebler approximation to the true DGP. In our implementation of the adaptive elastic net, we solve

\[
\hat{\Phi}_{\text{AEnet}} = \arg \min_{\Phi} \left[ \sum_{t=1}^{T} \left( X_t - \sum_{i=1}^{p} \Phi_i X_{t-1} \right)^2 + \lambda \sum_{i=1}^{p} \omega_i \left( |\Phi_i| + \frac{1}{2} \Phi_i^2 \right) \right]
\]

Where \( \omega_i = 1/|\Phi_{i,\text{old}}| \) and \( \lambda \) is selected equation by equation by 10-fold cross-validation. Note that the adaptive elastic net penalty averages the "LASSO penalty" with a "ridge penalty," moreover, that it weights the average by inverse ordinary least squares (OLS) parameter estimates, thereby shrinking the "smallest" OLS-estimated coefficients most heavily toward zero.

### 3.3. Block models

The Block model is a method to study network position and social roles (White et al., 1976). It is widely used to study specific issues (Breiger, 1976; Snyder and Kick, 1979; Shen et al., 2019; Zhang et al., 2020). A block model divides the actors in a network into several discrete subsets called "blocks" according to certain criteria (Wasserman and Faust, 1994) and investigates whether each block has a relationship. There are four role blocks: (i) brokers, the connections between their internal members are tiny, but members of this block both receive and send external relationships. (ii) main benefits, its members receive links not only from their own members but also from other blocks’ members. It is called isolated block when it has no connection with outside. (iii) main spillover, its members receive less external links from other blocks and send less links to their own members, while send more links to external members. (iv) bilateral spillover, members of this block send more links to inside and external members, while receiving few links from external. We give four kinds of spillover blocks by the evaluation indicators (Wasserman and Faust, 1994), as shown in Table 2.
Table 2
Four types of blocks.

| Internal linkages ratio | Received linkages ratio |
|-------------------------|-------------------------|
| < (m_k - 1)/(m - 1) | brokers |
| ≥ (m_k - 1)/(m - 1) | main benefit |
|                       | main spillover |
|                       | bilateral spillover |

Notes: There are n_k nodes in block M_k, then the number of possible relationships inside M_k is m_k(m_k - 1). The entire network contains m nodes, so all possible relationships among members in. are m(m - 1). In this way, we expect the total relationships expectation ratio of the block to be m_k(m_k - 1)/m(m - 1) = (m_k - 1)/(m - 1).

Table 3
Summary statistics of the EPU differences.

|              | Minimum | Median | Mean   | Maximum | Skewness | Kurtosis | Std. Dev. | JB test | ADF test |
|--------------|---------|--------|--------|---------|----------|----------|-----------|---------|----------|
| Australia    | -266.67 | -1.02  | 0.25   | 186.80  | -0.18    | 4.65     | 46.78     | 267.00  | 0.00     |
| Brazil       | -252.22 | 3.97   | 0.70   | 305.35  | 0.09     | 1.78     | 69.47     | 39.99   | 0.00     |
| Japan        | -173.90 | -1.31  | 0.53   | 230.41  | 0.59     | 2.91     | 55.30     | 120.96  | 0.00     |
| Chile        | -150.17 | 0.25   | 0.39   | 144.07  | 0.11     | 1.28     | 39.07     | 21.18   | 0.00     |
| China        | -286.06 | 0.47   | 1.54   | 276.87  | -0.12    | 4.78     | 58.61     | 281.63  | 0.00     |
| Colombia     | -102.34 | 0.70   | 0.38   | 135.21  | 0.52     | 1.95     | 33.01     | 60.49   | 0.00     |
| France       | -286.37 | -0.13  | 0.65   | 229.74  | -0.17    | 2.99     | 63.85     | 112.07  | 0.00     |
| Germany      | -165.24 | -1.06  | 0.42   | 322.54  | 0.69     | 3.51     | 58.38     | 174.61  | 0.00     |
| Greece       | -90.00  | 1.26   | -0.03  | 77.95   | -0.03    | 1.21     | 22.26     | 18.45   | 0.00     |
| India        | -181.21 | 1.53   | -0.09  | 155.68  | -0.27    | 4.26     | 35.37     | 226.38  | 0.00     |
| Ireland      | -158.81 | -1.99  | 0.49   | 245.45  | 0.36     | 1.06     | 59.49     | 20.61   | 0.00     |
| Italy        | -137.66 | 0.05   | 0.34   | 132.89  | 0.11     | 1.93     | 36.51     | 46.69   | 0.00     |
| Japan        | -105.93 | 0.18   | 0.04   | 93.67   | -0.12    | 3.94     | 24.59     | 191.78  | 0.00     |
| Korea        | -262.98 | -0.22  | 0.50   | 265.80  | 0.43     | 6.65     | 49.63     | 550.46  | 0.00     |
| Netherlands  | -110.64 | 0.35   | 0.13   | 186.14  | 0.56     | 4.25     | 32.84     | 237.14  | 0.00     |
| Russia       | -260.59 | -0.25  | 1.05   | 509.77  | 0.56     | 4.96     | 83.50     | 317.37  | 0.00     |
| Spain        | -68.84  | 1.21   | 0.42   | 115.71  | 1.03     | 5.62     | 19.80     | 438.99  | 0.00     |
| UK           | -683.11 | 0.29   | 0.51   | 371.42  | -1.75    | 23.14    | 78.59     | 6674.56 | 0.00     |
| US           | -203.72 | -1.79  | 0.66   | 209.59  | 0.24     | 5.59     | 43.78     | 386.20  | 0.00     |

Notes: JB represents the Jarque-Bera test statistics, and ADF means Augmented Dickey-Fuller test. Entry in parenthesis stands for the p-value.

3.4. Data

In this paper, we selected 19 countries to investigate the spillover effects of EPU on a global scale, including Australia(AU), Brazil(BR), Canada(CA), Chile(CL), China(CN), Colombia(CO), France(FR), Germany(DE), Greece(GR), India(IN), Ireland(IR), Italy(IT), Japan(JP), Korea(KR), Netherlands(NL), Russia(RU), Spain(ES), United Kingdom(UK), United States(US). The coverage of the sample spans the period January 1997 to January 2021. Table 3 reports the summary statistics of the EPU differences. The mean of the EPU difference values is positive, except for Greece and India. About half of the EPU indices have a positive median of difference values, while others are negative. This result implies different uncertainty behaviors for different countries in the sample period. In general, Russia has the most substantial standard deviation, measuring at 83.50. Thus, Russia has experienced drastic changes in EPU. United Kingdom stands out as the country with the highest kurtosis EPU differences during the sample period. Further, the non-normality and stationarity of the EPU differences are confirmed by the statistics from the Jarque-Bera test and Augmented Dickey-Fuller test.

The pairwise correlations between the changes of each country’s EPU are calculated, and the heat map is shown in Fig. 1. We find

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4 According to the latest world Bank data, Australia, Canada, France, Germany, Greece, Ireland, Italy, Japan, Korea, Netherlands, Spain, UK, and US are developed countries and others are developing countries.

5 According to COVID-19 Dashboard by the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University (JHU), As of January 31, 2021, the cumulative number of COVID-19 confirmed cases are ranked in the following order: United States, India, Brazil, United Kingdom, Russia, France, Spain, Italy, Turkey, Germany, where the United States and India have more than 10 million cases. The Cumulative number of deaths are ranked in the following order: United States, Brazil, Mexico, India, United Kingdom, Italy, France, Russia, Germany, Spain, where the United States, Brazil, Mexico and India have more than One hundred thousand.
that there is a positive correlation between EPU changes of most countries, and the US demonstrates high correlations with many countries, e.g., US-Germany(0.53), US-Korea(0.50), US-Canada(0.50).

4. Empirical results

4.1. Static analysis of spillover effects of global EPU

In this paper, the lag order of the VAR model determined by the AIC criterion is 2, and the period of variance decomposition of prediction error is set as 10. The method explained in Section 2 is applied using a rolling window of size 36 months; this means that we are computing the spillover indexes for 250 time periods, spanning from April 2000 to January 2021. Table 3 shows a static spillover analysis for the entire sample period where From and To is the directional reception spillover and transmission directional spillover index, respectively. The $ij$-th entry of this table can be read as the estimated contribution to the forecast error variance of country $i$ coming from innovation in country $j$.

Table 4 shows that EPU has significant characteristics of cross-country transmission. The uncertainty of a country’s economic policy is not only affected by its own factors, but also affected to a greater extent by the spillover impact of uncertainty in other countries. With the advancement of economic globalization, the economies of various countries are closely intertwined and forming an interconnected organic whole. When major uncertain events occur, a country’s government frequently changes relevant economic policies to prevent its economy from falling into recession, and the resulting uncertainty will spread to other countries.

It is noticeable that the EPU of United States makes the largest contribution to the overall spillovers in the system which indicates that the United States EPU has a significant impact on the whole system. Interestingly, the United States is also the biggest EPU receiver in the connectedness system. Bai et al. (2019) also found that the US seems to be both a major EPU spillover contributor and receiver among the analyzed sample. The main reason for this results may be that the United States, as one of the most developed and open countries, plays an important position in the global economic system. In terms of the transmission directional spillover index of EPU, there is a significant difference between the developed and developing countries. The average transmission directional spillover level of EPU in developed countries (58.14) is higher than that in developing countries (38.18). It follows that EPU in developed countries is more likely to spillover into other countries. The gap between countries affected by spillover effects of other countries’ economic policy uncertainties is relatively more minor.

![Fig. 1. Heat map of pairwise correlations of each sample’s EPU changes.](image-url)
Table 4
Connectedness table.

|    | AU  | BR  | CA  | CL  | CN  | CO  | FR  | DE  | GR  | IN  | IR  | IT  | JP  | KR  | NE  | RU  | ES  | UK  | US  | FROM |
|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| AU | 34.5| 2   | 5.4 | 5.3 | 2   | 2.8 | 3.4 | 6   | 4.5 | 4.7 | 0   | 1.4 | 8.2 | 2.4 | 2.8 | 0.8 | 2.9 | 4.5 | 6.1 | 65.5 |
| BR | 3.6 | 67.1| 2.4 | 1.6 | 2   | 2.8 | 2.6 | 2.5 | 0.6 | 1.7 | 0   | 0.4 | 2   | 0.9 | 2.4 | 1.1 | 1.9 | 0.4 | 4   | 32.9 |
| CA | 5.8 | 1.4 | 37.7| 2.7 | 0.8 | 3.4 | 4.5 | 8.7 | 2.3 | 2   | 0   | 1.8 | 4.5 | 3.5 | 3.6 | 0.5 | 2.2 | 4.3 | 10.3| 62.3 |
| CL | 6.2 | 1.8 | 2.8 | 41.4| 1.7 | 4.2 | 3.2 | 4.4 | 1.7 | 3.5 | 0.5 | 3   | 4.6 | 4.5 | 2.4 | 1.3 | 2.8 | 1.2 | 8.7 | 58.6 |
| CN | 1.7 | 1.3 | 2.1 | 1.6 | 63.3| 1.2 | 3.3 | 1.7 | 0.9 | 1.3 | 1.9 | 0.9 | 2.6 | 5.7 | 0.9 | 0.4 | 1.8 | 3   | 4.4 | 36.7 |
| CO | 3.5 | 1.8 | 3.9 | 4.5 | 1.1 | 44.3| 2.9 | 3.9 | 1.7 | 2.8 | 0.7 | 2.3 | 3.8 | 4   | 2.5 | 2.2 | 3.8 | 1.4 | 8.8 | 55.7 |
| FR | 3.8 | 1.5 | 4.5 | 3   | 2   | 2.6 | 38.3| 10.1| 1.5 | 0.6 | 0.6 | 3.3 | 2.9 | 5.8 | 4.1 | 1   | 3.2 | 5.4 | 5.7 | 61.7 |
| DE | 5.2 | 1.3 | 7.7 | 3.5 | 2   | 2.9 | 8.7 | 34  | 2.5 | 1.4 | 0.1 | 2.8 | 2.3 | 4.5 | 1.9 | 1.7 | 3.5 | 4.7 | 9.2 | 66  |
| GR | 6.9 | 0.7 | 3.4 | 2.4 | 0.6 | 2.3 | 2.2 | 4   | 53.4| 3.6 | 1.4 | 1.8 | 4.6 | 2.4 | 2.2 | 0.9 | 3.5 | 1   | 2.7 | 46.6 |
| IN | 6.1 | 1.3 | 2.7 | 3.8 | 0.4 | 2.9 | 0.8 | 2.1 | 3.6 | 52.3| 0   | 1.2 | 10.8| 1.7 | 2.1 | 1.2 | 2.2 | 1.8 | 0.8 | 1.5 | 25.5 |
| IR | 1.7 | 1   | 2.1 | 0.7 | 2.6 | 1.3 | 1.1 | 0.9 | 2.1 | 0.4 | 74.5| 1.1 | 0.8 | 2.1 | 1.2 | 2.2 | 1.8 | 0.8 | 1.5 | 25.5 |
| IT | 1.9 | 0.4 | 2.3 | 3.8 | 1.1 | 2.8 | 4.5 | 4.2 | 1.5 | 1.3 | 1.3 | 53.7| 2.6 | 3.1 | 4   | 1   | 3.7 | 2.6 | 4.1 | 46.3 |
| JP | 9.1 | 1.2 | 4.7 | 4.5 | 1.8 | 3.2 | 2.9 | 2.8 | 3.3 | 9   | 0.1 | 2   | 39.2| 1.9 | 4.1 | 1.3 | 2.8 | 1.7 | 4.4 | 60.8 |
| KR | 2.9 | 0.6 | 3.9 | 4.5 | 3.9 | 3.8 | 6.5 | 5.6 | 1.7 | 1.3 | 1.4 | 2.5 | 2   | 41.4| 1.4 | 0.9 | 0.5 | 4.6 | 10.6| 58.6 |
| NE | 3.6 | 1.7 | 3.1 | 2.5 | 0.6 | 2.5 | 5.7 | 2.9 | 1.5 | 1.8 | 0.3 | 3.9 | 4.4 | 1.6 | 48.1| 2.4 | 7.5 | 2.6 | 3.4 | 51.9 |
| RU | 0.8 | 1.3 | 1.1 | 1.4 | 0.2 | 2.4 | 1.9 | 3.2 | 0.8 | 1.3 | 1.1 | 2.4 | 1.9 | 1.4 | 2.4 | 6.2 | 7.7 | 0.3 | 3.4 | 33.8 |
| ES | 3.5 | 1.3 | 2.7 | 3.6 | 0.1 | 4.1 | 3.8 | 5.2 | 2.4 | 2.6 | 0   | 2.9 | 3.5 | 0.7 | 5.1 | 5.7 | 46.4| 0.9 | 5.3 | 53.6 |
| UK | 6.0 | 0.3 | 5.6 | 1.5 | 6.9 | 6.7 | 0.9 | 0.4 | 0.5 | 2.5 | 2.2 | 5.5 | 1.3 | 0   | 0.9 | 49.3| 4.8 | 50.7| 58.6 |
| US | 5.2 | 1.8 | 8.1 | 6.2 | 2.3 | 6   | 4.5 | 8.2 | 1.4 | 2.2 | 0.5 | 2.4 | 3.3 | 7.6 | 2.3 | 1.7 | 3.2 | 2.9 | 29.9| 70.1 |
| TO | 78.1| 22.8| 68.4| 57.3| 27.7| 52.6| 69.5| 83.3| 35  | 42.2| 10.3| 37.3| 67.1| 59.5| 46.9| 26.5| 56.2| 43.3| 101| 985.1|

Notes: This table presents the estimated contribution to the variance of the 10-day forecast variance error of country $i$ coming from differences to variable $j$. The diagonal elements ($i = j$) are the own differences shares estimates, which show the fraction of the forecast error variance of country $i$ from its own shocks. The last column, 'FROM' shows the total spillovers received by a particular country from all other countries, whereas the row 'TO' shows the spillover effect directed by a specific country to all other countries.
which makes the uncertainty of economic policies significantly different and leads to the significant fluctuation of their spillover levels. When the uncertainty of a country operation of their own economies, governments need to adjust their economic policies according to the actual economic conditions, while related countries will share the reception directional spillover effect, the fluctuation of reception directional spillover level of total spillover index of EPU has also significantly increased. Global and regional extreme events affect countries differently and in major events such as the UK’s "Brexit", China-US trade frictions, and COVID-19 outbreak have occurred frequently after 2016, and the total spillover index of EPU has also significantly increased. Global and regional extreme events affect countries differently and increase the uncertainty of their economic policies, which in turn spillover to other countries through a variety of channels.

Fig. 2 also tells us that extreme event shocks cause the total spillover index to rise significantly. This result supports the finding of Cui and Zhou (2020). The terrorist attack (911) in 2001 caused so much damage to the global economy that the total spillover index first peaked at 73.85% in January 2002. In 2007, the subprime mortgage crisis in the United States triggered the international financial crisis, and its vital destruction and impact made the global economy continue to downturn. Countries frequently introduced economic policies to stimulate economic recovery, and the total spillover index rose rapidly and reached 73.93% in December 2008. From 2010–2011, when the European sovereign debt crisis broke out, the total spillover index of EPU reached the highest level of 78.32%. Major events such as the UK’s "Brexit", China-US trade frictions, and COVID-19 outbreak have occurred frequently after 2016, and the total spillover index of EPU has also significantly increased. Global and regional extreme events affect countries differently and increase the uncertainty of their economic policies, which in turn spillover to other countries through a variety of channels.

Fig. 3 shows the transmission and reception directional spillover index respectively. The results indicate that the fluctuation of spillover index of the EPU of each country is significant differences. The transmission directional spillover level fluctuates wildly while the directional reception spillover is relatively stable. The difference further proves that the Cross-border spillovers of global EPU are real. The internal or external economic environment which a country suffered change over time. In order to maintain the smooth operation of their own economies, governments need to adjust their economic policies according to the actual economic conditions, which makes the uncertainty of economic policies significantly different and leads to the significant fluctuation of their spillover levels. When the uncertainty of a country’s economic policies increases significantly, the uncertainty will quickly spillover to other countries. While related countries will share the reception directional spillover effect, the fluctuation of reception directional spillover level of each country is relatively stable.

Fig. 3 also presents total net spillovers for individual countries. In these graphs, positive (negative) values at time t correspond to a net transmitter (receiver) position at that time. Clearly, the US, Australia, and Canada are net transmitters for most of the time implying that the relevant changes in the economic policies of the United States, Australia, and Canada will present a certain impact on other countries, while China, Ireland, and Russia are net receivers. For the sample period, other countries alternate between a net transmitter and a net receiver. Net spillovers exhibit great time-variation as well. For example, transmission from the United States to other countries increases significantly around the subprime mortgage crisis. Even Italy and Ireland become net receivers for that period.

We compare the net spillover effects during the SARS period from February 2003 to July 2003, Global financial crisis (GFC) from July 2007 to December 2009, and the COVID-19 period from January 2020 to January 2021 (Chang et al., 2020). Table 5 reports the net EPU indicators in the full-sample period and three phases. The absolute net spillover index in most countries is greater during COVID-19 epidemics than in other periods. We can also observe the changes in roles and importance for each country in different periods. United States is the most important contributor of uncertainties in the full sample, SARS and GFC period, which is consistent with most exiting literature (Klööner and Sekkel, 2014; Huang et al., 2018). While Germany is the center of EPU spillovers during the COVID-19 period. It is worth mentioning that China is not the primary source of spillover effect in the three phases even though it first reported the outbreak of COVID-19, different from the results of Li et al. (2021) which show that China is the center of EPU network.

In order to further clarify the dynamic characteristics of EPU spillover network, we took the average net spillover index between countries as the connection matrix to construct a spillover network during the SARS, GFC, and the COVID-19 period. Fig. 4 depicts the...
Fig. 3. Rolling-window plots of spillover indices. Notes: The black horizontal line represents $y = 0$. "from", "to", and "net" is the transmission directional spillover index, reception directional spillover index and net spillover index, respectively. Net spillover indexes are the difference between the uncertainty transmitted from one market to the system and the uncertainty received by that one market from the system. Hence when the index is positive, the market is a net transmitter of uncertainty, whereas it is negative, it is a net receiver of uncertainty.
global EPU spillover network with all the connections. The nodes in Fig. 4 represent countries, and the directed arrows connecting the two nodes represent the direction, where the arrow represents the direction of spillover, and the thickness of the line indicates the strength of net spillover relationship between each two countries. The thicker the line, the greater the net spillover strength. Fig. 4 shows that the network structure of global EPU spillover has certain time-varying characteristics, while it is less clear because of the large pairwise connections. To visualise the important connectedness and retain more information from the spillover network, we set the threshold value as 0.041, which is the same as the 50 quantile connection in the full sample period (Zhang et al., 2021).

Fig. 5 shows the EPU spillover network with threshold connections and Table 6 depicts the characteristics of these networks. The directional edges in the network have changed in different periods. In particular, COVID-19 period is greater than other periods. Affected by the break of global COVID-19 crisis, the clustering coefficient and density of network actually increased. This suggests that the closeness of various countries is higher and the correlation of economic policies between different countries increased during the COVID-19 epidemic. The COVID-19 epidemic made countries have to coordinate with each other to overcome this crisis (Li et al., 2021). During the global COVID-19 crisis, the average path length is smaller than GFC period, which means that the nodes in spillover network were more closely connected.

### 4.3. Block model analysis

Motivated by Zhang et al. (2020), we divide the block position of the EPU spillover network adjacency matrix using the UCinet software. And we choose the convergence criterion is 0.2 and the maximum separation depth is 2. Therefore, we get four spillover blocks, and the Appendix Table A1 shows the compositions of blocks in four periods. Table 7 presents the spatial connectedness and role analysis between EPU spillover blocks and indicates that four blocks’ roles and features are significantly different. Now we take the Full-sample period as examples to analyze EPU spatial linkages of 19 countries.

In the Full-sample period, the internal linkages and cross-linkages between the four blocks is 38 and 133, respectively. It shows that the spillovers between four blocks are very obvious. There are 52 sending relations in the first block, which the number of relations within the block is 10, and the receiving connections from other blocks are 28. The expected internal relation ratio is 22.22%, and the actual relation ratio is 19.23%. Thereby it is called "brokers block" which plays a role as a "bridge". It is important that strong spillover transmission between blocks may depend on the functions of "broker block" which maybe because of the mutual linkage between their members and other blocks’ members (Zhang et al., 2020). The sending link of the second block is 17, of which 3 internal links of this block, and it mainly sends the relationship to the other three blocks; the expected internal relation ratio and the actual relation ratio is 27.78%,17.24%, respectively. Thereby it is called "main spillover block". Members of the second block are United States, Japan, Korea, Australia, Germany, and France, which are mainly net transmitters. The sending link of the third block is 15, of which 3 links are in this block, the expected internal relation ratio and the actual relation ratio is 11.11%, 17.24%, respectively. Thereby it is called "Bilateral spillover block". The sending link in the fourth block is 15, and the internal links of this block is 10, while only 5 link send to third block, so it is called "main benefit block". Members of the fourth block are Greece, Russia, Netherlands, China, Ireland, indicating that these countries are more sensitive to external risk shocks. Overall, the internal links ratio of the fourth block is high, while the ratio of the second and third blocks is low.

We calculate each block’s density matrix and image matrix (shown in Table 8) to clearly reveal the spillover distribution. The overall density values which selected as the critical value of the EPU spillover network in Full-sample, SARS, GFC, and COVID-19 period are 0.025, 0.042, 0.036, and 0.045, respectively. If a block’s density is greater than the overall network density, the corresponding position in the image matrix is assigned 1; otherwise, the value is 0. The fluctuations within a block have significant

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**Table 5**

| Countries     | Full-sample | SARS | GFC | COVID-19 |
|---------------|-------------|------|-----|----------|
| Australia     | 0.71        | 0.24 | 0.76| -0.88    |
| Brazil        | -0.42       | -0.40| 0.20| -1.12    |
| Canada        | 0.51        | 1.07 | -0.72| 0.41     |
| Chile         | 0.31        | 0.10 | -0.09| 1.18     |
| China         | -0.84       | 0.00 | -0.70| 0.24     |
| Colombia      | 0.19        | -0.76| -0.19| -1.71    |
| France        | 0.34        | 0.46 | -0.41| 0.67     |
| Germany       | 0.45        | 0.71 | 0.26 | 2.18     |
| Greece        | -0.43       | 0.61 | 1.37 | -1.83    |
| India         | 0.03        | 0.74 | -0.42| -0.08    |
| Ireland       | -1.62       | -3.48| 0.27 | -0.96    |
| Italy         | -0.32       | 0.09 | 0.27 | -0.33    |
| Japan         | 0.75        | -0.70| 1.22 | 1.39     |
| Korea         | 0.79        | -1.39| -0.04| 0.66     |
| Netherlands   | -0.63       | 1.36 | 0.00 | -0.20    |
| Russia        | -1.31       | -1.99| -3.25| -0.10    |
| Spain         | -0.04       | 0.37 | 0.03 | 0.34     |
| United Kingdom| -0.02       | 0.72 | -0.14| -1.67    |
| United States | 1.55        | 2.27 | 1.59 | 1.81     |

Notes: This table shows the net EPU spillover index which represents the mean of dynamic net spillover index of each period.

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**Table 6**

| Countries | Full-sample | SARS | GFC | COVID-19 |
|-----------|-------------|------|-----|----------|
| United States | 1.55 | 2.27 | 1.59 | 1.81 |
| Brazil     | -0.42       | -0.40| 0.20| -1.12    |
| Canada     | 0.51        | 1.07 | -0.72| 0.41     |
| Chile      | 0.31        | 0.10 | -0.09| 1.18     |
| China      | -0.84       | 0.00 | -0.70| 0.24     |
| Colombia   | 0.19        | -0.76| -0.19| -1.71    |
| France     | 0.34        | 0.46 | -0.41| 0.67     |
| Germany    | 0.45        | 0.71 | 0.26 | 2.18     |
| Greece     | -0.43       | 0.61 | 1.37 | -1.83    |
| India      | 0.03        | 0.74 | -0.42| -0.08    |
| Ireland    | -1.62       | -3.48| 0.27 | -0.96    |
| Italy      | -0.32       | 0.09 | 0.27 | -0.33    |
| Japan      | 0.75        | -0.70| 1.22 | 1.39     |
| Korea      | 0.79        | -1.39| -0.04| 0.66     |
| Netherlands| -0.63       | 1.36 | 0.00 | -0.20    |
| Russia     | -1.31       | -1.99| -3.25| -0.10    |
| Spain      | -0.04       | 0.37 | 0.03 | 0.34     |
| United Kingdom | -0.02 | 0.72 | -0.14| -1.67    |
| United States | 1.55 | 2.27 | 1.59 | 1.81 |

Notes: This table shows the net EPU spillover index which represents the mean of dynamic net spillover index of each period.
correlation when the diagonal elements of the image matrix are 1. Fig. 6 displays the spillover transmission mechanism between four blocks and shows that the spatial connectedness between the EPU spillover blocks is different in different periods since the members and features of the blocks are also different. From Fig. 6(a) and 6(d), we can see that the fourth and the first block receives EPU spillover connections from the other three blocks, while the source of the EPU shock is the second and third block in Full-sample and COVID-19 period, respectively. Notably, Australia belongs to the main spillover block in the Full-sample period, while it is in the main benefit block in the COVID-19 period. This maybe because of the outbreak of COVID-19 pandemic.

4.4. COVID-19 impacts on spillovers

Based on the above findings, we further examine the impact of COVID-19 on spillovers using period during the COVID-19 epidemic (January 2020 to January 2021). We mainly consider the following facts: the number of new confirmed cases (Haroon and Rizvi, 2020) and deaths (Atri et al., 2021; Pham et al., 2021) are introduced to represent the severity of COVID-19. And we have school closing, workplace closing, and international movement restrictions to represent whether policies are adopted to respond to the event actively.

Table 9, Table 10, and Table 11 show the impacts of COVID-19 on reception directional spillovers, directional transmission spillovers and net spillovers. Overall, the results in columns 1 and 2 indicate that the new infection cases and deaths have a significant U-curve effect on reception and directional transmission spillovers, while there is no significant impact on net spillovers. As expected, although the outbreak of COVID-19 increases the magnitude of EPU spillovers, this effect gradually wears off as everyone progressively familiar with the event. However, when the event’s severity exceeds the critical point, it will increase the reception and transmission spillovers. This maybe because the COVID-19 pandemic increases the domestic uncertainties (Matuka, 2020), which may magnify the
impacts of the international spillovers of policy (Bernal et al., 2016).

In columns 3, 4, and 5, we show that the coefficients related to school closing and international movement restrictions are significant and positive in exploring the total EPU spillovers received by a particular country from all other countries and the EPU spillovers effect directed by a specific country to all other countries. And the international movement restrictions significantly increase the net EPU spillovers even if these policy measures of the COVID-19 pandemic reduced the density and connectivity of world trade (Vidya and Prabheesh, 2020). It’s worth exploring that the number of confirmed cases and deaths is not significant in determining the EPU spillovers’ magnitudes when adding policy measures variables.

Fig. 5. Global EPU spillover network of threshold connections.

Table 6
Network characteristics of EPU spillovers.

|                  | Clustering coefficient | Edges | Network density | Average path length |
|------------------|------------------------|-------|-----------------|--------------------|
| Full sample      | 0.517                  | 84    | 0.245           | 1.117              |
| SARS             | 0.652                  | 98    | 0.286           | 1.389              |
| GFC              | 0.611                  | 101   | 0.295           | 2.206              |
| COVID-19         | 0.738                  | 123   | 0.359           | 1.726              |

Notes: For the calculation of clustering coefficients, network density and average path length, please refer to Wu et al., 2021a.
### Table 7
Analysis of spatial spillovers and role between blocks in four periods.

| Blocks       | Receiving relationship | Number of members | Expected internal relation ratio (%) | Actual internal relation ratio (%) | Receive links from outside | Emit links to outside | Feature       |
|--------------|------------------------|-------------------|--------------------------------------|-----------------------------------|---------------------------|----------------------|---------------|
|              | First                  | Second            | Third                  | Fourth                           |                           |                       |               |
| Full-sample  | First                  | 10                | 26                    | 2                                  | 0                         | 28                   | 42            | brokers      |
|              | Second                 | 15                | 15                    | 16                                | 30                         | 15                   | 27.78         | Main spillover|
|              | Third                  | 2                 | 2                     | 3                                 | 10                         | 22.22                | 17.64         | Bilateral spillover|
|              | Fourth                 | 0                 | 0                     | 5                                 | 10                         | 11.11                | 19.23         | Main spillover|
| SARS         | First                  | 1                 | 14                    | 8                                 | 4                          | 5.56                 | 3.70          | Main benefit  |
|              | Second                 | 8                 | 55                    | 43                                | 18                         | 55.56                | 44.35         | Main spillover|
|              | Third                  | 0                 | 1                     | 6                                 | 3                          | 16.67                | 60            | Main benefit  |
|              | Fourth                 | 0                 | 4                     | 5                                 | 1                          | 5.56                 | 10            | Main benefit  |
| GFC          | First                  | 10                | 10                    | 21                                | 13                         | 22.22                | 18.51         | Main spillover|
|              | Second                 | 15                | 10                    | 27                                | 14                         | 22.22                | 15.15         | Main spillover|
|              | Third                  | 9                 | 3                     | 15                                | 5                          | 27.78                | 46.87         | Main benefit  |
|              | Fourth                 | 2                 | 1                     | 13                                | 3                          | 11.11                | 15.78         | Main benefit  |
| COVID-19     | First                  | 15                | 8                     | 1                                 | 3                          | 27.78                | 55.55         | Main benefit  |
|              | Second                 | 10                | 3                     | 1                                 | 15                         | 11.11                | 15            | Bilateral spillover|
|              | Third                  | 23                | 11                    | 6                                 | 23                         | 16.67                | 9.52          | Main spillover|
|              | Fourth                 | 33                | 12                    | 1                                 | 15                         | 27.78                | 24.59         | brokers      |

Notes: On the left side of Table 7, the diagonal elements present the internal relations of each block; the sum of each column (except for diagonal elements) indicates the external relations received from other blocks. Besides, this table also shows the number of members of each block, expected internal relation ratio, actual internal relation ratio and the block features.
5. Conclusions and policy implications

This study estimated the spillovers of EPU among 19 developed and emerging economies. We find that the transnational contagion of the EPU is significant and the total spillover index of EPU rises significantly under the impact of extreme events, which is in-line with the results of most exiting literature (Antonakakis et al., 2018; Bai et al., 2019; Jiang et al., 2019; Cui and Zhou, 2020). In contrast, countries with high correlation with extreme events have more substantial spillover effects. At the same time, the fluctuation of the transmission and reception directional spillover of EPU of each country is different. The directional transmission index fluctuates greatly while the reception directional spillover index is relatively stable. The characteristics of EPU spillover in developed and emerging economies involve different transmission mechanisms, which require different public policies.

Table 8
Density matrix and Image matrix among blocks.

|                | Density matrix | Image matrix |
|----------------|----------------|--------------|
|                | First          | Second       | Third         | Fourth        | First | Second | Third | Fourth |
| Full-sample    | 0.008          | 0.002        | 0.025         | 0.063         | 0     | 0      | 1     | 1      |
| (0.025)        | 0.035          | 0.015        | 0.052         | 0.094         | 1     | 0      | 1     | 1      |
|                | 0.001          | 0.003        | 0.012         | 0.039         | 0     | 0      | 0     | 1      |
|                | 0.000          | 0.000        | 0.007         | 0.019         | 0     | 0      | 0     | 0      |
| SARS           | 0.091          | 0.020        | 0.043         | 0.365         | 1     | 0      | 1     | 1      |
| (0.042)        | 0.012          | 0.024        | 0.144         | 0.048         | 0     | 0      | 1     | 1      |
|                | 0.000          | 0.002        | 0.039         | 0.054         | 0     | 0      | 0     | 1      |
|                | 0.000          | 0.002        | 0.056         | 0.075         | 0     | 0      | 1     | 1      |
| GFC            | 0.041          | 0.018        | 0.076         | 0.041         | 1     | 0      | 1     | 1      |
| (0.036)        | 0.036          | 0.012        | 0.079         | 0.112         | 1     | 0      | 1     | 1      |
|                | 0.013          | 0.004        | 0.039         | 0.009         | 0     | 0      | 1     | 0      |
|                | 0.005          | 0.005        | 0.034         | 0.030         | 0     | 0      | 0     | 0      |
| COVID-19       | 0.044          | 0.030        | 0.001         | 0.005         | 0     | 0      | 0     | 0      |
| (0.045)        | 0.046          | 0.032        | 0.001         | 0.007         | 1     | 0      | 0     | 0      |
|                | 0.133          | 0.092        | 0.029         | 0.090         | 1     | 1      | 0     | 1      |
|                | 0.119          | 0.036        | 0.001         | 0.017         | 1     | 0      | 0     | 0      |

Notes: This table shows that the density of EPU spillover network in the Full-sample, SARS, GFC, and COVID-19 period are 0.025, 0.042, 0.036, and 0.045, respectively. Take the Full-sample period as an example, if one block’s density is greater than 0.025, indicating that this block’s density is greater than the average level and the EPU spillover has a concentrate tendency in this block.

Fig. 6. spillover transmission mechanism between four blocks.
### Table 9
COVID-19 impacts on reception directional spillovers.

| Variables                        | (1)       | (2)       | (3)       | (4)       | (5)       |
|----------------------------------|-----------|-----------|-----------|-----------|-----------|
| confirmed                       | 2.77 **   | 0.21 ***  | 0.24 ***  | 0.17 ***  | 0.17 ***  |
|                                  | (1.18)    | (0.05)    | (0.09)    | (0.05)    | (0.05)    |
| deaths                          |           | 869.6 **  |           |           |           |
|                                  |           | (378.2)   |           |           |           |
| school_closing                  |           |           |           | 0.24 ***  | 0.24 ***  |
|                                  |           |           |           | (0.06)    | (0.06)    |
| workplace_closing               |           |           |           |           | 0.17 ***  |
|                                  |           |           |           | (0.11)    | (0.08)    |
| international movement restrictions|        |           |           |           |           |
|                                  |           |           |           |           |           |
| confirmed                       | 6.37 **   | -2.80     | -3.85     | -3.25     | -3.25     |
|                                  | (2.55)    | (2.67)    | (2.68)    | (2.66)    | (2.66)    |
| deaths                          | 289.2 **  | 204.7     | 286.1     | 233.65    |           |
|                                  | (112.4)   | (179.4)   | (179.8)   |           | (178.62)  |
| C                               | 3.31 ***  | 3.20 ***  | 3.93 ***  | 2.88 ***  |           |
|                                  | (0.06)    | (0.06)    | (0.11)    | (0.08)    | (0.13)    |

Notes: Standard errors are reported in parentheses. * Indicate the significance of t-statistics at 10%. * * Indicate the significance of t-statistics at 5%. * ** Indicate the significance of t-statistics at 1%.

### Table 10
COVID-19 impacts on transmission directional spillovers.

| Variables                        | (1)       | (2)       | (3)       | (4)       | (5)       |
|----------------------------------|-----------|-----------|-----------|-----------|-----------|
| confirmed                       | 3.73 **   | -0.22     |           | 0.34 ***  |           |
|                                  | (1.81)    | (0.14)    |           | (0.07)    |           |
| deaths                          | 991.4 *   | 0.23 ***  |           |           |           |
|                                  | (584.3)   | (0.08)    |           |           |           |
| school_closing                  |           |           |           |           |           |
| workplace_closing               |           |           |           |           |           |
| international movement restrictions|        |           |           |           |           |
|                                  |           |           |           |           |           |
| confirmed                       | 8.55 **   | -3.19     | -5.97     | -5.32     | -2.53     |
|                                  | (3.92)    | (4.18)    | (4.18)    | (4.04)    | (4.04)    |
| deaths                          | 333.5 *   | 237.8     | 449.2     | 176.54    |           |
|                                  | (173.7)   | (250.6)   | (279.7)   | (270.84)  |           |
| C                               | 3.32 ***  | 3.20 ***  | 3.45 ***  | 2.46 ***  |           |
|                                  | (0.09)    | (0.09)    | (0.18)    | (0.20)    |           |

Notes: Standard errors are reported in parentheses. * Indicate the significance of t-statistics at 10%. * * Indicate the significance of t-statistics at 5%. * ** Indicate the significance of t-statistics at 1%.

### Table 11
COVID-19 impacts on net spillovers.

| Variables                        | (1)       | (2)       | (3)       | (4)       | (5)       |
|----------------------------------|-----------|-----------|-----------|-----------|-----------|
| confirmed                       | 0.97      | 0.023     | -0.47 *** | 0.16 *    |           |
|                                  | (2.08)    | (0.09)    | (0.16)    | (0.05)    |           |
| deaths                          |           |           |           |           |           |
| school_closing                  | 1218      |           |           |           |           |
|                                  | (6709)    |           |           |           |           |
| workplace_closing               |           |           |           |           |           |
| international movement restrictions|        |           |           |           |           |
|                                  |           |           |           |           |           |
| confirmed                       | 2.19      | -0.39     | -2.11     | 0.72      |           |
|                                  | (4.51)    | (4.86)    | (4.73)    | (4.79)    |           |
| deaths                          | 44.24     | 33.05     | 163.1     | -57.11    |           |
|                                  | (199)     | (336.2)   | (331.6)   | (321.58)  |           |
| C                               | 0.00      | 0.00      | -0.04     | 0.27 *    | -0.42 *   |
|                                  | (0.11)    | (0.11)    | (0.21)    | (0.14)    | (0.24)    |

Notes: Standard errors are reported in parentheses. * Indicate the significance of t-statistics at 10%. * * Indicate the significance of t-statistics at 5%. * ** Indicate the significance of t-statistics at 1%.
developing countries are different. The former’s transmission directional spillover is much higher than the latter, while the gap of directional reception spillover is small.

Moreover, we use block models to analyze the transmission mechanism of EPU. The results show that the EPU network can be divided into four spillover blocks, which can more clearly reflect EPU spillover distribution and roles of relevant countries in the process of EPU transmission. The role of blocks and the spatial spillover transmission path between EPU blocks is different in different periods.

The absolute of net spillover index in most countries are greater during the COVID-19 epidemics than the full sample, SARS, and GFC period. China is not the primary source of spillover effect even though it first reported the outbreak of COVID-19, different with the results of Li et al. (2021). The severity of COVID-19 has a significant U-curve effect on reception and transmission directional EPU spillovers, while there is no significant impact on net spillovers. The policy measure of international movement restrictions during the COVID-19 period significantly increases the directional and net EPU spillovers. While the number of new confirmed cases and deaths is not significant in determining the EPU spillovers’ magnitudes when adding policy measures variables.

These results will be of particular interest to scholars concerned about the impact of COVID-19 crisis on the spillover effect of EPU; as well as to policy-makers and market regulators seeking to interpret how changes in economic policies in other countries may affect the implementation effect of the established and future economic policies. In addition, our findings have the following policy implications for countries on reducing the transnational spillover of EPU. Firstly, the spillover effect of a country’s EPU is affected by both domestic and foreign influential factors. Therefore, the regulatory authorities of various countries should establish an all-around and deep-seated regulatory concept and take the initiative to resolve the negative impact of EPU on their own economy. This means that the regulatory authorities should maintain the stable operation of the domestic economy and pay attention to the economic operation of all countries worldwide and actively take effective measures to avoid extreme events in other countries.

Secondly, the spillover effects of EPU among countries are also affected by the global major event shocks (E.g., SARS, Covid-19, GFC, etc.). Therefore, the regulatory authorities should improve information disclosure and guide the public’s reasonable expectations. Meanwhile, the risk monitoring, early warning system, and early intervention mechanism should also be enhanced to prevent the extremely negative impact on the financial market caused by the sharp surge of panic caused by major public emergencies.

Thirdly, the major international emergencies in different periods have different impacts on the economy. Thus, the governments should strengthen the communication of relevant policies among countries, adopt differentiated regulatory tools and targeted policy objectives, establish a coordination mechanism of macroeconomic policies. All in all, with the global epidemic not eliminated, the stable development of the global economy needs the joint efforts of all countries. Future research can focus on the mechanism and influencing factors of transnational EPU spillovers, so as to better maintain global economic stability.

CRediT authorship contribution statement

Yuqin Zhou: Conceptualization, Methodology, Visualization, Writing, Editing. Zhenhua Liu: Data curation, Software, Writing. Shan Wu: Supervision, Data curation, Software, Methodology, Writing.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

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Declaration of interest statement

No conflict of interest exists in the submission of this manuscript, and the manuscript is approved by all authors for publication. I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed.

Appendix A

See appendix Tables. A1 and A2.
Table A1
Members of each block.

| Block   | First block                                      | Second block                                   | Third block                                    | Fourth block                                |
|---------|--------------------------------------------------|-----------------------------------------------|-----------------------------------------------|--------------------------------------------|
| Full-sample | Canada, United Kingdom, Spain, Chile, Colombia | United States, Japan, Korea, Australia, Germany, France | Brazil, India, Italy                           | Greece, Russia, Netherlands, China, Ireland |
| SARS    | India, Netherlands                               | Germany, Australia, United States, China, France, Greece, United Kingdom, Canada, Italy, Chile, Spain | Brazil, Colombia, Korea, Ireland              | Austria, Belgium, China, Japan              |
| GFC     | United States, Netherlands, Germany, Korea, Brazil| Australia, Japan, Greece, Italy, Ireland       | India, Colombia, Spain, France, Russia, United Kingdom | Canada, China, Chile                       |
| COVID-19 | China, United Kingdom, Colombia, Brazil, Australia, Greece | Ireland, India, Italy                         | Germany, Japan, United States, Chile          | Spain, Canada, Russia, Netherlands, Korea, France |

Notes: This table gives the members of the four blocks in four periods.

Table A2
Variables- definitions.

| Variable          | Definition                                                                 |
|-------------------|-----------------------------------------------------------------------------|
| confirmed         | Monthly increased number of confirmed cases. (% of total population)         |
| confirmed2        | The square of the confirmed cases                                           |
| deaths            | Monthly increased number of deaths. (% of total population)                 |
| deaths2           | The square of the deaths                                                    |
| school closing    | 0: No measures 1: Recommend closing 2: Require closing (only some levels or categories, eg just high school, or just public schools 3: Require closing all levels |
| workplace closing | 0: No measures 1: Recommend closing (or work from home) 2: require closing for some sectors or categories of workers 3: require closing (or work from home) all-but-essential workplaces (eg grocery stores, doctors) |
| international movement restrictions | 0: No measures 1: Screening 2: Quarantine arrivals from high-risk regions 3: Ban on high-risk regions 4: Total border closure |

Notes: The school closing, workplace closing and international movement restrictions take the last day of each month as the standard. All of these indicators computed based on the variables come from Guidotti and Ardia (2020), and More details can be seen in the Guidotti and Ardia (2020).

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