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Research paper

Does COVID-19 pandemic event alter the dependence structure breaks between crude oil and stock markets in Europe and America

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\begin{abstract}
This article attempts to investigate the influence of novel coronavirus (COVID-19) pandemic on the dependence structure break between crude oil and stock markets in Europe and America using ARMA-GARCH and R-vine copula methods. The empirical results demonstrate that international crude oil and European (American) stock markets have significant asymmetric and symmetric dependence structure, rapid outbreak of COVID-19 pandemic triggers their dependence structure break. The results of Kendall correlation confirms that COVID-19 pandemic amplifies the dependence risks between European Brent crude oil and France (German and Spain) stock markets and reduces the dependence risk between Brent crude oil and UK (Italy) stock markets after February 20, 2020. The COVID-19 pandemic may amplify the dependence risk between West Texas Intermediate (WTI) crude oil and Canada stock markets after March 23, 2020, it first quickly reduces the dependence risks between WTI crude oil and US (Brazil and Mexico) stock markets after March 23, 2020 and then enlarges their dependence risks after June 30, 2020. European and American crude oil and stock markets have induced different ranges of their dependence risks in different time scales and their dependence structure breaks have good robustness.
\end{abstract}

\section{Introduction}

The World Health Organization identified the novel coronavirus (COVID-19) pandemic is an international concerned public health emergence on January 31, 2020. Novel coronavirus epidemic is the largest public health emergence in the past 100 years, and the COVID-19 pandemic event has created a greater influence on the economic growth, society and human health in the global countries or regions with rapid expansion of COVID-19 pandemic. It is also a global pandemic with the fastest spread, the widest range and the most stringent prevention and control measures. With quick spread and outbreak of the COVID-19 epidemic, Asia, Europe and America have gradually become the epicenter of the COVID-19 pandemic, different countries have shown different expansion and development trend with its rapid outbreak. On August 14, 2020, the accumulative COVID-19 confirmed cases in the global countries and regions are 21,4049 million, and the cumulative death cases are 769,546 thousand. The United States (US), Brazil, India, Russia, South Africa, Peru, Mexico, Colombia, Spain, Chile have become the most severely top 10 countries with the highest cumulative COVID-19 confirmed cases.

Various severe prevention and control measures of COVID-19 epidemic induced a greater decline of global economic output, larger reduction of social consumption and investment, higher restrictions of cross-border trade and foreign investment and blockages in corporate supply chains and cracks in industrial value, and then resulted in greater decline of effective market demand. For example, different trade embargo from COVID-19 pandemic event brings about greater supply chain shocks, blocked industrial chain system, which cause untimely supply of raw materials, the time inability to deliver products etc (Goel et al., 2020; Shi et al., 2021). The outbreak of COVID-19 pandemic brought about greater shocks of China's economy and its economic growth rate fluctuated dramatically, which resulted in the variance being relatively high (Zhao and Lin, 2022). The continuous expansion of the COVID-19 epidemic have led to weaker global economic growth and a sharp decline of global oil demand, higher negative market shocks in the global energy and stock markets, which resulted in greater crash risk in international oil price and stock price, and amplified risk contagion risk between oil and stock markets. The main purpose of this article investigates whether the COVID-19 epidemic as greater public health emergency is triggered the change in the dependence structure between crude oil and stock markets in European and American countries.

Many literatures confirm that the crude oil and stock markets in the developed and emerging countries may have dependence...
structure and risk contagion effects. Crude oil price and international stock markets exhibit different dependence structure in European and Asian countries and oil-producing net exporters and net importers (Lai et al., 2011; Bouri, 2015a,b; Mokni, 2020). Oil price shocks have an asymmetric influence on the stock market (Sim and Zhou, 2015; Raza et al., 2016; Al-hajj et al., 2018; Alamirg and Amin, 2021; Tuna et al., 2021). Crude oil price and global and sectoral renewable energy indices indicate significant time-varying and symmetric tail dependence (Reboredo, 2015; Ahmad, 2017; Song et al., 2019; Uddin et al., 2019; Khan et al., 2021). Extreme upward and downward oil price changes more significantly affect the upper and lower stock price in major developed economies and the five BRICS countries (Aloui et al., 2013; Reboredo and Ugolini, 2016; Kocaarslan and Soytas, 2019). Chinese industry stock and global crude oil markets have stronger risk contagion in recessions or bearish markets (Zhu et al., 2016).

Moreover, financial crisis and economic recession produce greater impacts on the returns in crude oil and stock markets. Commodity Futures Trading Commission’s (CFTC) announcements can affect the stock returns of oil and gas companies during the 2008 financial crisis (Berk and Rauch, 2016). Crude oil prices and stock market returns have a weak positive dependence before the global financial crisis and increased dependence in the aftermath of the crisis (Mollick and Assefa, 2013; Zhu et al., 2014; Bouri, et al. 2015; Yang et al., 2015; Jammazi and Reboredo, 2016; Jebran et al., 2017; Ferreira et al., 2019). The dependence level between the BRIC stock market and the international crude oil market tends to increase dramatically during the financial crisis, and the simultaneous booms between two markets decrease after the crisis (Pan, 2014; Chen and Ly, 2015). Within the financial crisis and post-crisis, the responses of US stock returns to oil price shocks are heterogeneous for different manufacturing industries (Tsai, 2015). The 2008 financial crisis produces the structural changes of time-varying long-term correlation between the crude oil and US stock markets (Fang et al., 2018; Hashmi et al., 2021). The financial crisis and the European debt crisis manifest most acutely the dependences between the crude oil and China (US) stock markets (Bampinas and Panagiotaidis, 2017; Junttila et al., 2018; Li and Wei, 2018; Yu et al., 2020). The crude oil and the US stock markets produce extreme tail asymmetric nexus in the uncertainty of economic policy (Zha and Zhang, 2013; Bekiros and Uddin, 2017; Wen et al., 2019). Special market situation, geopolitical risks, macroeconomic fundamentals and domestic policies influence significantly time-varying dependences and risk spillovers between crude oil and stock returns in all the BRICS countries (Wei et al., 2019; Ji et al., 2020a,b; Li et al., 2020). The mutual leading relationships of both European carbon (melta) and crude oil markets are especially sensitive during abnormal political events and periods of financial recession and global emergency (Kaushik, 2018; Wu et al., 2021).

Policy uncertainty and public event also affect the nexus between crude oil and stock markets. Energy future returns have nonlinear causal dependence with economic policy uncertainty, stock market returns and implied volatility (Andreassen et al., 2016; Dutta et al., 2021). Gold and crude oil are safe-haven assets against extreme down movements in clean energy stock market (Elie et al., 2019). A daily newspaper-based index of uncertainty related with infectious diseases produces a significant impact on oil-market price volatility (Bouri et al., 2020). The ongoing COVID-19 pandemic produces unprecedented demand and supply shocks in global energy markets (Bento et al., 2021). Rising (falling) oil prices and economic policy uncertainty may produce asymmetric influences on global stock returns, highly related to stock market conditions and financial crisis (You et al., 2017; Fei et al., 2020). As international concerned public health event, the COVID-19 pandemic event has created more significant influences on global financial market and crude oil market. The COVID-19 outbreak has caused the stock markets fell quickly in major affected countries and areas, such as Japan, Korea, the US, Germany, Italy, and the UK etc (Harjoto et al., 2020; Liu et al., 2020a,b). Chinese industries and the Asian stock markets have been severely affected by the novel coronavirus outbreak (He et al., 2020; Liu et al., 2020a,b). The COVID-19 and crude oil price shocks may produce the unprecedented impacts on geopolitical risk, economic policy uncertainty and extreme stock market volatility (Sharifa et al., 2020; Salisu et al., 2021). The COVID-19 pandemic induces international crude oil prices the presence of chaotic and nonlinear behavior (Bildiri et al., 2020; Mensi et al., 2020; Manejek et al., 2021). The COVID-19 pandemic has a great effect on the cross-correlation between crude oil and agricultural future markets (Wang et al., 2020). The oversee COVID-19 pandemic in Asia, Europe and America has a shown rapid and continuous expansion, indicating international, complexity and quick deterioration trends. A sharp decline of global energy demand, induced international crude oil price and global stock price crash.

Previous relevant literatures demonstrate that financial and political crisis and policy uncertainty exacerbate the risk contagion effects between the oil market and the stock market (Aloui and Ben Aissa, 2016; Jammazi and Reboredo, 2016; Bekiros and Uddin, 2017; Han and Zhou, 2017; BenSaida, 2018; Song et al., 2019). One limitation of the extant studies is their inability to capture time-varying dependence structure breaks under different market shocks induced by different public health events. Another limitation is their inability to capture risk contagion effects cross the crude oil and stock markets in Europe and America under the different market state in different time horizons. In order to fill these perceived gaps, this study extends the previous literatures in three ways as follows: First, we extend Aloui et al. (2013), Mensi et al. (2017) and Ji et al. (2020a,b) by examining the dependence structure between the crude oil and stock markets, the COVID-19 epidemic as crucial public health emergence significantly alters the time-varying dependence structure breaks between the crude oil and stock markets in European and American countries, our findings suggest the COVID-19 epidemic event could be a pivotal link to the international crude oil and stock markets. Second, we extend Yang et al. (2015) and Dai et al. (2020) by time-varying dependence methods, this article uses an enhanced methodology called ARMA-GARCH and multivariate R-vine (C-vine) copula methods to reveal the heterogeneity patterns of dependence structure breaks in different time horizons between the crude oil and stock markets, and rapid changes in the confirmed cases of COVID-19 epidemic may induce crucial dependence structure break points to crude oil and stock markets in the different time scales. Third, we extend the existing literature in suggesting risk contagion patterns to international crude oil and stock markets, their dynamic pair-wise copula demonstrates the dependence structure and asymmetric tail dependence are temporal during the severe COVID-19 epidemic emergence, the risk contagion effects in international crude oil and stock markets reveal further time-varying and time-scale trends.

Considering the related discussion limitations and research gaps, this article has three main novelties compared with previous studies. First, Our empirical results demonstrate that the returns of international oil futures and specific stock markets in Europe and America exhibit significant volatility clustering effects, European (American) stock and IPE (WTI) oil futures markets display asymmetric and symmetric time-varying dependence structure in the period considered using ARMA-GARCH and R-vine copula model. Our results have greater divergence with Mensi et al. (2017)’s and Gafnaoui (2019)’s results, which
time-varying dependence structure has several variance regimes between oil and stock markets. Second, we also find rapid outbreak of COVID-19 pandemic significantly corrects the time-varying dependence structure breaks and risk contagion ranges between IPE (WTI) crude oil futures and the Europe (America) stock markets after February 20, 2020 (March 23, 2020 and June 30, 2020). Our finding provide new evidence asymmetric time-varying dependence structure break and demonstrate public COVID-19 pandemic makes significant time-varying dependence structure break between oil and stock markets, which are different with volatility dependence structure break among different stock markets (Luo and Chen, 2018). Finally, the results of the Kendall correlation demonstrate that the COVID-19 pandemic can enlarge the dependence risks between IPE oil and France (Spain and German) stock markets, and reduce the dependence risk between IPE oil and UK (Italy) stock markets in Europe, moreover, the COVID-19 pandemic may quickly decrease the dependence risks between WTI oil and US (Brazil and Mexico) stock markets after March 23, 2020 and then quickly amply the dependence risks after June 30, 2020, while boost the dependence risks between WTI oil and the Canada stock markets after the first and second structure break point. Some studies show Financial crisis and great recession induce the dynamic multidimensional dependence structure between crude energy commodity and stock markets (Aloui et al., 2013; Aloui and Ben Aissa, 2016; Li and Wei, 2018). Our findings demonstrate that rapid changing of COVID-19 pandemic trigger the time-varying dependence risk between crude oil and stock markets in America and Europe, which are greatly different from the results of Alousi, et al. (2013). Alouri and Ben Aissa (2016) and Li and Wei (2018). Finally, their time-scales of dependence structure breaks between international oil and stock markets have good robustness using C-vine copula model.

The other sections are organized as follows: Section 2 analyzes the transmission mechanism of COVID-19 pandemic on the international crude oil and specific stock markets. Section 3 presents the time-varying R-vine copula models. Data source and descriptive statistics are shown in Section 4. The empirical results of time-varying marginal distribution and the dependence structure break triggered by rapid outbreak of COVID-19 pandemic are reported in Section 5. And the main results are concluded in Section 6.

2. Transmission mechanism of COVID-19 pandemic

2.1. Transmission mechanism of COVID-19 pandemic on stock market

In an effective market, all valuable information will be timely and accurately reflected in the future trend of the stock price ranges (Urquhart and Mcgroaty, 2016; Mills and Salaga, 2018). Rapid outbreak of COVID-19 pandemic has a significant impact on the global macroeconomic growth, such as economic output and social consumption decreased, international trade restricted, industrial development suffered loss, financial institution risk intensified short-run global market fluctuation increased etc. The COVID-19 epidemic harms the division of labor in the global value chain, leads to greater uncertainty of total supply and demand, deteriorates the employment circumstance, raises the unemployment ratio and inflation risks.

Those severe COVID-19 pandemic prevention and control measures may result in massive corporation shutdown, insufficient production, blocked supply chain and industrial chain, untimely products delivery, international order cancellation, output stagnated or fell sharply, and corporate operating income and expected profit fell sharply. Different types of organizations have greater differences in anti-stress and anti-risk capabilities, and have different flexibility in return-to-work, return-to-produce and market operations. The COVID-19 also brings a series of unfavorable factors to small and medium-sized companies, such as the decline in market demand and operating income, the increase of production costs and debt repayment, and the tightness of cash flow. The unfavorable factors influences expected operating capitals and profitable ability. This effective information will be reflected in the corporation stock price, the decline of expected profitability will induce the decline of corporation stock price.

The negative concerns and reports of the public and emerging new media often produce significant impacts on investor sentiment and stock market shocks (Sun et al., 2016; Huang, 2018). Rumors may disrupt the information environment in the capital markets, which are not conducive the effective allocation of financial resource. The COVID-19 pandemic is the greatest public health event in recent 100 years, the public media frequently and extensively reports a great amount of negative news on the COVID-19 pandemic rumors, false information and negative public opinions, for example, continuous increase of COVID-19 confirmed cases and death cases, rapid outbreak of COVID-19 pandemic, stagnated economic growth, blocked international trade, and severe shocks of global stock markets etc. Those negative reports may produce fear, astoundment and bad emotion of market investors, and stock market price reflect the investor expectations and sentiments (Papakryiakou et al., 2019). Those poor market sentiments may create excessive concerns of market investor and order trade imbalance, and produce overreaction and severe shocks of global stock markets.

2.2. Transmission mechanism of COVID-19 pandemic on correcting oil-stock dependence

Early literatures demonstrate that financial and political crisis, policy uncertainty are the major fundamentals of global stock market shocks. The COVID-19 pandemic creates huge market shocks of international crude oil price and global stock markets. Variegated COVID-19 prevention and control measures taken by governments of global countries severely creates the sharp decline of the whole social output and consumption, leads to the cliff-like decline of total energy demand in global countries, triggering a plunge in international crude oil prices. The COVID-19 pandemic triggers the macroeconomic recession and international trade congestion, monetary, fiscal and economic policies produce greater uncertainty, and further promotes the sharp decrease of international crude oil price and global stock markets price. The US COVID-19 pandemic exhibits a rapid and continuous deterioration following China, Korea, Iran, Italy. The US stock markets are the main sources of risk contagion on the stock market for developed and emerging economies, the worsening COVID-19 pandemic induces a sharp fall US crude oil price and stock market price, which quickly trigger larger risk contagion of international crude oil price and global stock market price (Alqahtani et al., 2021). The continuous deterioration of global COVID-19 aggravates the greater uncertainty the economic policies and geopolitical risks, and it induces greater uncertainty of total oil supply and demand in various countries and then further enhances the risk contagion effect between international crude oil and global stock markets (Sharifa et al., 2020). Rumors, false information and negative public opinions on COVID-19-related, economic policy uncertainty and economic recession further trigger the interactions between international crude oil and global stock markets (Atri et al., 2021). Unexpected information triggers the bad investor sentiments among different investors, causes noise traders to produce irrational transactions, and then promote greater market overreaction and fluctuations in international crude oil and global stock markets.
### 3. Dynamic R-vine copula modeling framework

General GARCH, VAR-Copula, Extreme Value Theory and GARCH-Copula methods are to investigate the volatility spillover and dependence structure between crude oil and stock markets (Aloui et al., 2013; Chen and Lv, 2015; Mensi et al., 2017; Mokni and Youssef, 2019; Ji et al., 2020a,b; Yu et al., 2020). The stock market and crude oil market stimulate rapid and continual fluctuation of their market dependencies during and aftermath of the 2008 Financial Crisis (Yu et al., 2020), after the oil price collapse and demand shocks circumstance (Ji et al., 2020a,b) and in different stock market conditions (Reboredo and Ugolini, 2018).

In this section, this article presents direct and indirect risk transmission channels and measures the time-varying asymmetric dependence between Europe and America stock markets and international crude oil markets using time-varying R-vine copula model. This section provides four steps. First, we begin with modeling the density margins of the Europe and America stock and crude oil price returns series by simulating the appropriate ARMA-GARCH specifications extracting the standardized residuals. Second, we present the conceptual structure figures of R-vine copula model, adopt the empirical cumulative distribution function (ECDF) and evaluate the selected copula models. Third, we identify how we measure the structure break of oil-stock market dependence, precipitated by novel coronavirus pandemic event using likelihood method and asymptotic distribution. Four, we investigate the dependence and risk contagion effects between the paired markets over each of the identified temporal sub-divisions before and after COVID-19 pandemic event.

#### 3.1. The margin distribution measure

The international crude oil price and stock price are generally characterized by high kurtosis and fat tail, auto-correlation and volatility clustering effect. To estimate the margin distribution of the stock and crude oil price returns series, we present the suitable econometric model to obtain the daily serial of filtered returns. We combine the standard GARCH (k,l) with an ARMA(P,Q) process by Bollerslev (1986). The GARCH model has larger benefits to capture high kurtosis and fat tail, and thus measure the margin distribution in order to transform the international crude oil and stock price returns, catering the selection of suitable copula model. Our measure is able to capture non-linear characteristics of the international crude oil price and stock price, and ensure the appropriate evaluation of the dynamic copula model and further R-vine copula model. Given that the standardized residuals of time series follow the standard distribution, an ARMA(P,Q)-GARCH(k,l) model can be expressed as:

\[
\begin{align*}
\sigma_t^2 &= \alpha \epsilon_{t-1}^2 + \beta \sigma_{t-1}^2 \\
\epsilon_t &= \sigma_t \epsilon_t
\end{align*}
\]

where \( \sigma_t \) is the returns series of the international crude oil price and stock price at time \( t \), which is measured by using \( \sigma_t = \ln p_t - \ln p_{t-1} \), here \( p_t \) is the international crude oil price and stock price returns series respectively. \( a, b \) is the coefficients of the returns autoregression and residual errors respectively. \( P \) denotes the lagged order of autoregression vector. \( Q \) denotes the lagged order of moving average vector. \( \mu_t \) is a sequence of a normal distribution of random variable with zero mean and unit variance. \( \sigma_t \) is the conditional variance of price returns series, which depend on the previous returns residual \( \epsilon_{t-j} \) and previous conditional variance \( \sigma_{t-j}^2 \). \( \alpha, \beta \) is the coefficient of ARCH and GARCH components respectively, \( \alpha \geq 0, \beta \geq 0, k \) is the order of previous returns residual, \( l \) is the order of previous conditional variance. We capture the optimal lag length for the conditional mean and conditional variance (ARMA) model by the minimum Akaike information criterion (AIC).

#### 3.2. Time-varying R-vine copula model

On the basis of Joe (1997) specification, the R-vine copula model is used to capture the multiple variable dependence structure between international crude oil price and stock price in Europe and America. The vine copula model is to measure a hierarchical structure composed of a set of bivariate copulas that capture the dependence nexus between two variables to describe the high-dimensional joint distribution. This empirical method provides flexibility in modeling because the paired marginal variables are independent. Introduced by Aas et al. (2009), pair-copula construction is that the joint density function of multivariate variable can be decomposed into the product of both a series of pair-copula density functions and marginal distribution functions, considering the n-dimensional random variable vector. Pair copula construction is facilitated to recognize the needed pairs of variables and their set of conditional variables through an array of trees. Vine trees can arrange the \( n(n-1)/2 \) paired copulas of an n-dimensional pair copula construction in \( n-1 \) linked trees. Its multivariate joint density function can be expressed as:

\[
\begin{align*}
&f(x_1, x_2, \ldots, x_n) = \int_\mathbb{R} \int_\mathbb{R} \cdots \int_\mathbb{R} f(x_n | x_{n-1}) f(x_{n-1} | x_{n-2}) \cdots f(x_1 | x_2) f(x_2) \cdots f(x_n) \\
&\quad \times f(x_n) f(x_{n-1}) f(x_{n-2}) \cdots f(x_2) f(x_1)
\end{align*}
\]

where \( f_i \) is the marginal densities, \( n = 1, 2, \ldots, n \), \( X = (x_1, x_2, \ldots, x_n) \) are n-dimensional random variables, \( f(x_1, x_2, \ldots, x_n) \) is a multivariate joint density function.

A n-dimension copula is a function C that link multivariate distributions to their univariate marginal distribution functions. Let \( x_1, x_2, \ldots, x_n \) be stochastic variable with the marginal distribution function \( F_1, F_2, \ldots, F_n \), respectively, then there exists a copula C, the multivariate joint density distribution can be written as:

\[
\begin{align*}
f(x_1, x_2, \ldots, x_n) &= C(F_1(x_1), \ldots, F_n(x_n)) \times \prod_{i=1}^{n} f_i(x_i)
\end{align*}
\]

where \( F(F_1, F_2, \ldots, F_n) \) is a vector of continuous invertible distribution functions, \( C(F_1(x_1), \ldots, F_n(x_n)) \) is the conditional copula function. Each conditional density function can be decomposed as:

\[
\begin{align*}
f(x | v) &= C_{x | v} (F(x | v_{-j}), F_i(v_{-j})) \times f(x | v_{-j})
\end{align*}
\]

Here \( v_j \) is the jth vector in n-dimension vectors, \( v_{-j} \) is the \( n-1 \) dimension vectors except \( v_j \) vector, \( C_{x | v} (\ldots) \) refers to each pair-copula density function, which contains a pair of conditional distribution function \( f(x | v) \). The pair-copula density function can be also measured as:

\[
\begin{align*}
\frac{\partial C_{x | v}(x | v_{-j})}{\partial F_i(v_{-j})} \times f(x | v_{-j})
\end{align*}
\]
and autocorrelation. R-vine copula model can measure the dependence between multiple variables, and has greater flexibility and diversity than other C-vine and D-vine models. R-vine copula function introduces a new concept edge, it not only selects the variety of copula models, but also obtains more information about conditional relevance from correcting R-vine structure.

Based on the description of Bedford and Cooke (2002) and Kurowicka and Cooke (2006), the R-vine contains a series of trees, and each side of every tree has a conditional pair-copula. A n-dimensional R-vine copula is composed of n \times (n-1) bivariate copula in an n - 1 level tree form, and is denoted by T_1, T_2, . . . , T_{n-1}, the T_i-tree node set is N_i, and its edge set is E_i(i = 1, 2, . . . , n - 1), satisfying as follows:

(1) T_i-tree node set N_i = \{1, 2, . . . , n\}, its edge set is E_i.

(2) T_j-tree node set N_j = E_{i-1}(1, 2, . . . , n - 1), it implies that the i-tree node set is the edge set of i - 1 tree.

(3) If the two edges in the T_i-tree are related by the edges in the T_{i+1}-tree and the two edges have common node in the T_i-tree. Accordingly, a simple R-vine copula with five variables and four trees are shown in Fig. 1.

In Fig. 1, the first level of the tree in this five-dimensional R-vine structure, such as pair (1,5)(2,1),(2,3) and (4,2) will be evaluated. In the second level of tree, we estimate the pair (1,3 | 2), (2,5 | 1) and (4,3 | 2) and so on.

We assume the edge e = [j(e) \times k(e) | D(e)] in the edge set E, here j(e), k(e) are the two conditional nodes connected with the edge e, D(e) is the conditional set e. The marginal density of ith variable X_i is f_i(i = 1, 2, . . . , n), and then a R-vine distribution is measured as the joint probability density function f(x_1, x_2, . . . , x_n) with the random variable X = (X_1, X_2, . . . , X_n) (Reboredo and Ugolini, 2018).

\[
f(x_1, x_2, \ldots, x_n) = \prod_{k=1}^{n} f_k(x_k) \prod_{i=1}^{n-1} \prod_{e \in E_i} C_{j(e),k(e)} f(K_{j(e)})(F(x_{j(e)})).
\]

\[
F(Y_{j(e)})|X_{(X)} = \prod_{k=1}^{n} f_k(x_k) \prod_{i=1}^{n-1} \prod_{e \in E_i} C_{j(e),k(e)} f(K_{j(e)})(F(x_{j(e)})),
\]

where N = (N_1, N_2, . . . , N_{n-1}) refers to the nodes set, E_i = (E_1, . . . , E_n) refers to the edges set, x_0(e) refers to the sub-vector of random variable x, contained in the conditional set D(e), C_{j(e),k(e)}(0|K) the copula density function with the corresponding edge e. We choose the appropriate R-vine structure using the maximum spanning tree in order to solve the optimal problem for each tree.

\[
\max \sum_{e \in (i,j)} |t_{ij}|
\]

where t_0 is the Kendall correlation coefficient of the two edges between i and j in spanning tree, which is a tree on all the nodes. The maximum spanning tree is obtained by the static empirical Kendall correlation estimation.

This article simulates the marginal distribution using the ARMA-GARCH model, and then the standardized residual errors are converted into a uniform distribution of (0, 1), and finally the related coefficients are estimated by the maximum likelihood method. The specific measure is estimated as follows: First, we estimate the Kendall correlation coefficient between two returns series, and use the maximum spanning tree (absolute value) method to determine the structure of the first tree; Second, we select the appropriate copula function of the first tree by comparing the Akaike information criterion (AIC); Third, we use the copula function of the first tree to determine the conditional observations and determine the structure of the second tree by the maximum spanning tree method; Fourth, we determine all the structures by continuously iterating method and the parameter coefficients of the appropriate copula model by calculating the maximum likelihood method (see Table 1).

3.3 Structure break of R-vine copula function

In order to investigate the effect of COVID-19 pandemic event on the dependence structure between international crude oil and global stock markets, this article examines their dependence structure break using R-vine copula function. Here assumed total study period is T, i observational value is x_i = (x_{i1}, x_{i2}, . . . , x_{in}), if the dependence between international crude oil and global stock markets exists structure break, we provide the following hypothesis.

\[H_0: \Theta_1 = \Theta_2 = \cdots = \Theta_T\]

\[H_1: \Theta_1 = \Theta_2 = \cdots = \Theta_i \neq \Theta_{i+1} = \cdots = \Theta_T\]
where \( \lambda \) is the number of the parameter in the copula. The number of total samples series is written.

\[
-2 \ln A_t = 2 \left( \sum_{i=1}^{t} \log \text{lik}(x_i, \hat{\Theta}_i) + \sum_{j=t+1}^{T} \log \text{lik}(x_j, \hat{\Theta}_j) \right)
\]

where \( \text{lik}(\cdot) \) denotes the logarithmic likelihood function estimated by maximum likelihood method.

\[
\hat{\lambda}_t = \max_{1 \leq c < t} \left(-2 \ln A_t \right)
\]

If the statistical value \( \hat{\lambda}_t \) is larger, the testable results reject the null hypothesis, the international crude oil and global stock markets exhibit significant dependence structure break point, the corresponding structure break point is trade date when \(-2 \ln A_t \) is the maximum. The hypothesis test of structure break point is estimated by the specific maximum likelihood method. When \( x \to \infty \), the asymptotic distribution \( \hat{\lambda}_t^{1/2} \) can be expressed as follows:

\[
P(\hat{\lambda}_t^{1/2} > x) \approx \frac{x^p \exp \left( -\frac{x^2}{2} \right)}{2^{p/2} \Gamma(p/2)} \times \left( \ln \left( \frac{1 - U}{1 - L} \right) \frac{UL}{U L} \right) \times \left( 1 - \frac{p}{2} \frac{D}{x^2} + \frac{x^2}{4} + O \left( \frac{1}{x^4} \right) \right)
\]

where \( U(T) = L(T) = (\ln T)^{3/2}/T \), \( U, L \) are the upper tail dependence and lower tail dependence, \( p \) is the number of the parameter in the \( \Theta \), \( T \) is the number of total study period. This article examines whether the dependence structure between international crude oil and global stock markets exhibits a structure break point by the above mentioned asymptotic distribution. If the null hypothesis is rejected, novel coronavirus pandemic event may trigger the dependence structure break point between international crude oil and global stock markets, and their structure break period is \( \hat{\tau} = \arg \max \left(-2 \ln A_t \right) \). Otherwise, the null hypothesis is accepted, their dependence cannot exist a structure break point. If there are multiple structure break point in the study sample series, this article detects the structure break point by dichotomy method. When the international crude oil and global stock markets exhibit the first structure break point, we split total samples series into two sub-samples based on the maximum structure break point period, and then examine the structure break point of each sub-samples and find the second structure break point, and those analysis continues until there do not yet produce the newly structure break point in each subsequence.

4. Data source and descriptive statistics

4.1. Data source

Currently, many countries in Asia, Europe and America are the most serious area influenced by novel coronavirus pandemic event. Accumulative COVID-19 confirmed cases and death cases in Germany, France, the United Kingdom, Italy and Spain are the earliest and most critical countries in Europe, meantime, cumulative covid-19 confirmed infection cases and death cases in the United States, Canada, Mexico and Brazil are also the most critical countries in America. US, Canada, Mexico, Brazil, Germany, France, UK, Italy and Spain are the member states in G20, which have higher economic development level. Here, this article selects the NASDAQ (National Association of Securities Deal Automated Quotations) Stock Indices, Toronto 300 Stock Indices in Canada, Mexico MXX Stock Indices and Brazil IBOVESP A Stock Indices as study samples of America stock market, which are the most representative stock trade markets in four countries in America. And this article chooses the German DAX Stock Indices, FranceCAC Stock Indices, UK FTSE 100 Stock Indices, daily Italy FTSE MIB Stock Indices and Spain IBEX35 Stock Indices as study samples of Europe stock markets. This article selects the daily future price of Brent crude oil in UK London Intercontinental Exchange (ICE) and daily futures price of West Texas Intermediate (WTI)

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light sweet oil in US New York Mercantile Exchange as study samples of international crude oil markets, which are the two benchmark prices in international crude oil markets. ICE is the most important Exchange for energy futures and options products in Europe, and one of the global crude oil transaction centers. The crude oil futures price in London ICE is a barometer for observing the trend of crude oil prices in the international oil markets.

In order to more effectively investigate the dependence structure between international crude oil and Europe (America) stock markets, this article selects the daily closing prices of stock indices in specific countries of Europe and America and the daily closing price of ICE Brent (IPE) oil futures and US WTI light sweet oil futures. Here we assume that \( p_t \) is the closing price of stock indices in specific countries of Europe (America) and the closing price of ICE and WTI oil futures, their returns \( r_t \) is defined as \( r_t = \ln(p_t/p_{t-1}) \). This article selects their returns to investigate the dependence structure between different stock indices and international crude oil markets. This article investigates whether novel coronavirus pandemic event influences the dependence structure break between international crude oil and Europe (America) stock markets, and introduces the range ratio of daily increased COVID-19 confirmed cases in specific countries of Europe and America, their range ratio is defined as \( \ln(COVID_{t}/COVID_{t-1}) \), here \( COVID_{t} \) is the sum of daily increased COVID-19 confirmed cases in specific countries of Europe and America. The study period covers in the period from January 2, 2019 to August 14, 2020, total samples have 399 actual daily series after deducting statutory holidays and weekends. The stock indices in America and Europe and two oil futures prices are sourced from China Stock Market & Accounting Research (CSMAR) Database and Wind database, their daily increased COVID-19 confirmed cases are sourced from Wind database.

4.2. Descriptive statistics of related variables

Table 2 indicates the descriptive statistics and Ljung-Box test of related returns both stock indices and international crude oil in Europe and America. Fig. 2 shows the daily returns of the stock indices in specific countries of Europe and America, and their daily returns have similar dynamic trends. In Europe, the means daily returns are positive for German DAX, France CAC and Italy MIB stock indices, and the means daily returns are negative for UK FTSE and Spain IBEX stock indices as well as IPE crude futures oil. The standard deviations of the stock indices returns in German, France, UK, Italy and Spain of Europe are 0.0168, 0.0165, 0.0149, 0.0182 and 0.0168, and their stock indices returns exhibit similar variances. However, the standard deviation of IPE oil future price returns is 0.0351, and it exhibit higher variance than the stock indices returns in specific five countries of Europe. In America, the mean daily returns are positive for US NDAQ, Brazil IBOV and Canada TSX stock indices in America, while the mean daily returns are negative for Mexico MXX stock indices and WTI oil futures price. The standard deviation of WTI oil futures price returns is larger than that of the stock indices returns for specific countries in America. For the returns of crude oil futures prices and the stock indices in Europe and America, their skewness are less than zero, and their kurtosis are larger than 3.0000, the returns of the stock indices and crude oil futures price in Europe and America exhibit obvious left tail and steeper kurtosis. Fig. 3 shows the daily returns of Brent and WTI oil futures price, and their returns exhibit a similar time-varying trend in the period considered.

Fig. 4 shows the daily increased COVID-19 confirmed cases for specific countries in Europe and America and their sum of daily COVID-19 confirmed cases in Europe and America. In Europe, daily COVID-19 confirmed cases in German, France, UK, Italy and Spain keep an increasing trend in the period from mid-February 2020 to End-March 2020, and then contain a decline trend in the period from April 2020 to mid-July 2020, finally hold a rising trend after mid-July 2020. In America, daily COVID-19 confirmed cases in US, Brazil, Canada and Mexico contain greater divergence, daily COVID-19 confirmed cases in US and Brazil keep a surprising increase, while daily COVID-19 confirmed cases in Canada contain a slow increase, then decrease, finally hold a smooth changes, daily COVID-19 confirmed cases maintain a gradual augment in the period from March 2020 to August 2020. The sum of daily COVID-19 confirmed case confirm that COVID-19 pandemic in Europe first increase, then decrease, while COVID-19 pandemic in America maintain a surprising augment after March 2020.

### Table 2

| Statistics | DAX | CAC | FTSE | MIB | IBEX | IPE |
|------------|-----|-----|------|-----|------|-----|
| Mean       | 0.0405 | 0.0001 | −0.003 | 0.0002 | −0.0005 | −0.0004 |
| Maximum    | 0.1041 | 0.0806 | 0.0867 | 0.0855 | 0.0753 | 0.1545 |
| Minimum    | −0.1305 | −0.1310 | −0.1151 | −0.1854 | −0.1515 | −0.3086 |
| Std. Dev.  | 0.0168 | 0.0165 | 0.0164 | 0.0182 | 0.0168 | 0.0351 |
| Skewness   | −0.9024 | −1.5806 | −1.2890 | −3.2002 | −2.0354 | −2.0472 |
| Kurtosis   | 15.4560 | 14.2858 | 13.7895 | 32.2275 | 19.6133 | 21.2055 |

| J-B        | 4073.9 | 3601.7 | 3311.4 | 18144 | 6747.4 | 7842.7 |
| Q(20)      | [0.000] | [0.000] | [0.000] | [0.000] | [0.000] | [0.000] |

Note: Std. Dev. Denotes the standard deviation of related variables, J-B denotes the Jarque Bera statistical value. Q(20) is the Ljung-Box statistical value for serial correlation in related returns with 20 lags. Probability statistical values are reported in square parentheses for the last two tests.
5. Empirical results of COVID-19 pandemic event affecting the oil-stock dependence

This section investigates the impacts of COVID-19 pandemic events on the dependence structure break between Europe (America) stock and IPE (WTI) oil markets using time-varying R-vine copula model. There are four steps as follows: first, we evaluate the marginal distribution of the returns both stock and oil markets after filtering the returns by ARMA-GARCH model; second, we select the appropriate copula function and measure the R-vine dependence structure and risk contagion effects both stock and oil markets; third, we analyze the oil-stock dependence structure break point triggered by novel coronavirus pandemic event; fourth, we measure the parameter coefficients of R-vine copula function and the Kendall correlation coefficients after novel coronavirus pandemic event.

5.1. Marginal distribution estimation

We first filter the returns of Europe (America) stock indices and IPE (WTI) oil prices and extract their standardized residual errors using appropriate ARMA (p,q)-GARCH (1,1) process. The objectives are to obtain the standardized residuals after deducting the impacts of conditional heteroscedasticity. Tables 3 and 4 report the estimated results of marginal distribution of the returns both Europe (America) stock indices and IPE (WTI) oil markets. On the basis of the maximum likelihood value and the Akaike information criterion (AIC), the minimum values for the AIC are used to select the most appropriate means and lags of ARMA-GARCH model, the returns both Europe (America) stock indices and IPE (WTI) oil futures prices perform the optimal results of their marginal distributions.

As shown in Table 3, in Europe, the returns of UK FTSE stock indices exhibit a significant autoregressive and moving average trend, implying the average returns exhibit a significant dependence structure. While other returns of IPE oil futures prices and German DAX, France CAC, Italy MIB and Spain IBEX stock indices have non-significant autoregressive and moving average trend in the period considered, implying the above mentioned average returns have non-significant dependences. All the coefficients of $\alpha$ and $\beta$ for the returns of five stock indices and IPE oil futures price exhibit significance at the 1% significant level, they have significant ARCH and GARCH effects, implying previous residual errors and conditional volatility produce significant impacts on current conditional volatility. Their coefficients of ARCH effects are far less than the coefficients of GARCH effects, these results

Fig. 2. The daily returns of the stock indices in Europe and America.

Fig. 3. The daily returns of WTI and Brent oil futures price.

Fig. 4. The daily increased COVID-19 confirmed cases in Europe and America.
demonstrate that previous residual errors have lower impacts on current conditional volatility than previous conditional volatility. The coefficients of $\alpha + \beta$ are 0.976, 0.977, 0.989, 0.984, 0.974 and 0.999 respectively for the DAX, CAC, FTSE, MIB, IBEX stock indices and IPE oil futures price, which have significant volatility clustering effects in the period considered. Their LB and LB2 tests have greater statistical values, their probabilities are larger than 0.05, those results demonstrate that the residual errors and squared residual errors do not have autoregressive trends. The coefficients of Engle’s tests have greater statistical values, their average returns do not have correlation series, and the resultsof ARCH-LM tests confirm that their residual errors do not have ARCH effects. All the estimated results demonstrate that the residual errors and probability values in the square parentheses are less than 0.05, the null hypothesis is rejected.

5.2. Dependence structure estimation both Europe (America) stock and IPE (WTI) oil markets

This section selects the optimal R-vine copula model on the basis of the Kendall’s tau estimation of each pair variables using the probabilistic integral transformation of the standard residual errors for the marginal distribution of each variable. The evaluated results of the coefficients of parameters and Kendall correlation in R-vine copula model are shown in Table 5 and Fig. 5 for IPE oil futures and the stock market in specific five countries of Europe. We choose the appropriate copula model based on the statistical value of Akaike information criterion (AIC). In the first tree, we select the skewed-t copula model to evaluate the dependence between France CAC and German DAX (Italy MIB) stock indices, their coefficients of par and par 2 parameters imply that they have symmetric lower and upper tail dependence at the 5% significant level. We select the survival Gumbel copula to evaluate the dependence between France CAC and UK FTSE stock indices as well as between IPE oil futures and France CAC (Spain IBEX) stock indices, their coefficients of par parameter reflect that they have asymmetric upper tail dependence at the 5% significant level. In the second tree, selecting the France stock market as the center node in Europe stock markets, the coefficients of parameter par and Kendall tau confirm that German DAX and Italy MIB stock markets exhibit asymmetric lower tail dependence at the 5% significant level, while Italy MIB stock and IPE oil markets exhibit a symmetric lower and upper tail dependences at the 5% significant level. European Stock and oil markets exhibit a significant and positive dependence and risk contagion (Aloui et al., 2013; Zhu et al., 2016), financial crisis
Table 4
The estimated results of marginal distribution of the returns both America stock and WTI oil markets.

|       | NDAQ | IBOV | TSX  | MXX  | WTI  |
|-------|------|------|------|------|------|
| $\phi_0$ | 0.002*** | 0.001* | 0.001 | 0.000 | 0.002 |
|       | (5.795) | (1.876) | (1.265) | (0.073) | (1.565) |
| $\phi_1$ | 0.650*** | 1.179*** | (2.749) | (74.242) | 0.872*** |
|       | (0.750) | (4.793) | (0.073) | (1.561) | (1.3848) |
| $\phi_2$ | 0.084 | $-0.287^{**}$ | 0.001 | 0.000 | 0.000 |
|       | (5.795) | (1.876) | (1.265) | (0.073) | (1.565) |
| $\phi_3$ | $-0.848^{***}$ | $-1.278^{**}$ | 0.002 | 0.000 | 0.000 |
|       | (51.132) | (1.493) | (11.143) | (1.561) | (1.3848) |
| Variance | $\omega$ | 0.000 | 0.000*** | 0.000 | 0.000*** | 0.000*** |
|       | (0.337) | (2.669) | (0.331) | (3.741) | (3.111) |
| $\alpha$ | 0.288*** | 0.141*** | 0.365*** | 0.165*** | 0.378*** |
|       | (3.02) | (4.653) | (5.944) | (4.256) | (5.14) |
| $\beta$ | 0.711*** | 0.809*** | 0.634*** | 0.782*** | 0.621*** |
|       | (4.411) | (19.015) | (29.377) | (9.848) | (9.848) |
| Likelihood | 1190.735 | 1079.723 | 1394.036 | 1234.144 | 829.3978 |
| AIC | $-2371.47$ | $-2149.446$ | $-2782.072$ | $-2466.288$ | $-1648.7956$ |
| LB | 13.851 | 9.743 | 2.627 | 4.360 | 6.957 |
| LB2 | 2.097 | 4.569 | 0.762 | 5.552 | 6.740 |
| ARCH-LM | 1.841 | 0.953 | 0.446 | 6.466 | 1.293 |

Note: 1.***,**,* denote the significance at the 1%, 5% and 10% significant level respectively, the values in the parentheses are z-statistical values; 2. LB, LB2 denote the Ljung–Box statistical values of the correlation log-likelihood value for the residual errors and squared residual errors in the ARMA-GARCH model; 3. ARCHLM denotes the Engle’s LM test of the ARCH effects for those residual errors, and probability values in the square parentheses are less than 0.05, the null hypothesis is rejected.

Our findings confirm that increased COVID-19 pandemic induce significant and asymmetric tail dependence structure between oil and stock market in France and Spanish except Italy, which are greater divergence compared with the above Alouie et al. (2013), Zhu et al. (2016) and Reboredo and Ugolini (2016).

Table 6 and Fig. 6 show the evaluated results of the coefficient of parameter par (par2) and Kendall tau correlation using R-vine copula model in America. In the first tree, the coefficients of parameter par and Kendall tau correlation demonstrate that US NSAQ stock and WTI oil exhibit a symmetric zero-tail dependence at the 5% significant level, while the dependence of stock markets both US NSAQ and Brazil IBOV, both US NSAQ and Canada TSX, makes extreme upward and downward oil price varies on upper and lower stock price quantiles (Reboredo and Ugolini, 2016).
Table 5
The estimated results of the coefficients of parameters and Kendall correlation in R-vine copula in Europe.

| Tree | Edge | Copula     | par   | par2    | tau     | Loglik  | AIC   |
|------|------|------------|-------|---------|---------|---------|-------|
| 1    | 2,1 t | t          | 0.901** (0.012) | 4.044** (1.058) | 0.714   | 356.919 | −709.838 |
|      | 2,4 t | t          | 0.840** (0.020) | 3.086** (0.696) | 0.635   | 283.091 | −562.182 |
|      | 2,3 Survival Gumbel | Survival Gumbel | 2.519** (0.145) | 0.714   | 356.919 | −709.838 |
|      | 6,2 Survival Gumbel | Survival Gumbel | 2.788** (0.163) | 0.641   | 257.133 | −512.266 |
|      | 6,5 Survival Gumbel | Survival Gumbel | 1.321** (0.058) | 0.243   | 29.293  | −56.586 |
| 2    | 4,1;2 Survival Gumbel | Survival Gumbel | 1.243** (0.052) | 0.195   | 21.688  | −41.376 |
|      | 6,4;2 t | t          | 0.346** (0.052) | 9.759** (3.313) | 0.225   | 29.443  | −54.886 |
|      | 3,1 Survival Gumbel | Survival Gumbel | −0.077 (0.056) | 0.603   | 223.765 | −445.530 |
|      | 4,3 Survival Gumbel | Survival Gumbel | 1.392** (0.064) | 0.103   | 4.645   | −7.290 |
| 3    | 5,2;6 Frank | Frank | 0.587 (0.311) | 0.065   | 1.807   | −1.614 |
|      | 6,1;4,2 Frank | Frank | 0.612 (0.328) | 0.067   | 1.948   | −1.897 |
|      | 3,4;6 Frank | Frank | 0.351 (0.324) | 0.039   | 0.614   | 0.773 |
|      | 5,3;6 Frank | Frank | 0.937** (0.303) | 0.130   | 4.645   | −7.290 |
| 4    | 3,5;2,1 t | t          | 0.173** (0.053) | 0.111   | 6.014   | −10.028 |
|      | 4,2;3 Frank | Frank | 0.944** (0.316) | 0.128   | 8.173   | −14.347 |
| 5    | 5,1;3,6,4,2 Normal | Normal | −0.036 (0.053) | −0.023  | 0.273   | 1.454 |

Note: 1,2,3,4,5,6 refer to German DAX, France CAC40, UK FTSE 100, Italy FTSE MIB and Spain IBEX35 Stock Indices as well as IPE oil futures Price; the values in the parentheses are the standard errors in the par and par2 estimations; AIC refers to the Akaike information criterion.

Table 6
The estimated results of the coefficients of parameter and Kendall correlation in R-vine copula in America.

| Tree | Edge | Copula     | par   | par2    | tau     | likelihood | AIC   |
|------|------|------------|-------|---------|---------|-----------|-------|
| 1    | 1,5 Frank | Frank | 2.273** (0.337) | 0.235   | 24.611   | −47.221 |
|      | 1,2 Survival Gumbel | Survival Gumbel | 1.399** (0.063) | 0.285   | 46.446   | −90.893 |
|      | 3,1 Survival Gumbel | Survival Gumbel | 1.948** (0.103) | 0.056   | 2.908    | −3.815 |
|      | 4,3 Survival Gumbel | Survival Gumbel | 1.392** (0.064) | −0.224  | 0.185    | 1.631 |
| 2    | 2,5;1 Gaussian | Gaussian | 0.173** (0.053) | 0.111   | 6.014    | −10.028 |
|      | 3,2;1 Survival Gumbel | Survival Gumbel | 1.147** (0.064) | 0.128   | 8.173    | −14.347 |
|      | 4,1;3 Frank | Frank | 0.944** (0.316) | 0.130   | 4.645    | −7.290 |
| 3    | 3,5;2,1 t | t          | 0.173** (0.053) | 0.111   | 6.014    | −10.028 |
|      | 4,2;3 Frank | Frank | 1.506** (0.313) | 0.160   | 11.468   | −20.936 |
| 4    | 4,3;3,2 Gaussian | Gaussian | 0.069(0.054) | 0.044   | 1.506    | −1.012 |

Note: 1,2,3,4,5 refer to US NASQ, Brazil IBOV, Canada TSX and Mexico MXX Stock Indices as well as WTI oil futures Price; the values in the parentheses are the standard errors in the par and par2 estimations.

Both Canada TSX and Mexico MXX exhibit asymmetric lower tails at the 5% significant level. In the second tree, Brazil IBOV stock market and WTI oil market exhibits symmetric zero-tail dependence at the 5% significant level, and their risk spillover is contagious by the US NASQ stock market. Canada TSX and Brazil IBOV stock markets exhibit asymmetric lower tail dependence at the 5% significant level, and their risk spillover is contagious by the US stock market. The US NASQ and Mexico stock markets have symmetric zero-tail dependence at the 5% significant level, and their risk spillover is contagious by the Canada stock market. Oil and stock markets in USA, Canada and Brazil exhibit a asymmetric tail dependence structure after financial crisis (Reboredo and Ugolini, 2016; Ji et al., 2020a,b; Cui et al., 2021), while our results find that WTI oil and stock markets in USA and Brazil have a symmetric tail dependence structure after increased COVID-19 pandemic event.
5.3. Dependence structure break point triggered by COVID-19 pandemic event

In order to investigate the stock-oil dependence structure break point triggered by COVID-19 pandemic event, this article measures the dependence structure break point between IPE (WTI) oil futures and specific stock markets in Europe and America using the likelihood ratio method. First, this article examines the dependence structure break point test for the whole samples in the period and measures the maximum $\lambda_t$ value in R-vine copula model using formula (8), and the dynamic $\lambda_t$ values are shown in Fig. 7. Second, the maximum $\lambda_t$ value is 72.600 on February 20, 2020 in Fig. 7, their probability of evaluated results are less than 0.010 on the basis of the asymptotic distribution in the formula (9), accordingly, the R-vine dependence have a significant structure break point on February 20, 2020. Third, we split the whole samples into two sub-samples before and after February 20, 2020, and examine the structure break point test for two sub-samples, and finally, we cannot find the second significant structure break point. The COVID-19 pandemic in Europe exhibits a rapid outbreak, especially, daily COVID-19 confirmed cases in Italy, Spanish, UK, German and France have quickly expanded, the market panic triggered by COVID-19 pandemic event has gradually contagious in the stock market and IPE crude oil futures markets, and then results in the dependence structure break between oil futures and specific stock markets, influencing the stability of financial markets in specific countries of Europe. In Fig. 7, IPE oil future market and France CAC (Spain IBEX) stock market have significant dependence structure break point on February 20, 2020, and IPE oil futures market and Italy MIB (UK FTSE) stock market yet have significant dependence structure break point on February 20, 2020 through France stock market, and IPE oil futures market and German DAX stock market produced significant structure break point on February 20, 2020 through France and Italy stock markets. Especially, after February 20, 2020, their time-varying dependence both IPE oil and France (UK) stock markets exhibit a significantly increasing trend, and their time-varying dependencies between IPE oil and German (Italy, Spain) stock markets have significant fluctuations. Their time-varying IPE-CAC dependences are greater than IPE-IBEX and IPE-MIB dependence, and their time-varying IPE-FTSE and IPE-DAX dependences are the lowest after the European COVID-19 pandemic event. Financial crisis induces time-varying dependence structure break between the Brent oil and stock markets in the Central and Eastern European (Aloui et al., 2013). However, increased COVID-19 pandemic event causes the time-varying dependence structure break between IPE oil and stock markets in Europe on February 20, 2020.

In Fig. 8, the results of the structure break test demonstrate that the maximum $\lambda_t$ value is 43.480 on June 30, 2020, its probability is less than 0.001, accordingly, American stock market and crude oil future market have significant structure break points on June 30, 2020 using R-vine copula function. We split the whole samples into two sub-samples, and examine the structure break points for two sub-samples using the dichotomy method. The second maximum $\lambda_t$ value is 30.350 on March 23, 2020, and its probability is less than 0.030, accordingly, we find that the American stock market and oil market yet exhibit the second significant structure break point on March 23, 2020. Seen from Fig. 4, the accumulative COVID-19 confirmed cases in America have a rapid increase in March and June 2020 respectively, the suddenly quick outbreak of American COVID-19 pandemic may induce the drastic variance of WTI oil futures prices and specific stock indices in America, and then correct their dependence break point. After the COVID-19 pandemic event, the dependence both WTI oil and American stock markets have twice structure break point on March 23, 2020 and June 30, 2020 respectively, their time-varying Kendall correlation exhibit a fast decline, then a ephemeral increase and finally a quick decrease in America. The time-varying Kendall correlation both WTI oil futures and US NDAQ stock markets drops down after March 23, 2020 and then maintains a certain market fluctuation from June to August in 2020. The time-varying Kendall correlation both WTI oil futures and Brazil IBOV stock market quickly descends after March 23, 2020 and then tardily increases after June 30, 2020, their WTI-IBOV risk spillover is contagious by the US stock markets. The dynamic Kendall correlation both WTI oil futures and Canada TSX (Mexico MXX) stock markets maintains lower market shocks and their oil-stock risk spillovers are contagious by US and Brazil stock markets. WTI oil and USA and Chinese stock markets vary dynamically across the structural break periods (Zhu et al., 2016; Yu et al., 2020). However, our results find that increased COVID-19 pandemic event induce the twice breaks of time-varying dependence structure between WTI oil and stock market in America during the period from January 1, 2020 and June 30, 2020.
5.4. Oil-stock dependence change after their structure break point

Tables 7 and 8 show the estimated results of the dependence ranges between oil futures and stock markets in Europe and America after the COVID-19 pandemic event using R-vine copula function. In Table 7, the Kendall correlation coefficient both IPE oil futures and France CAC stock markets is 0.579 in the period from January 2, 2019 to February 20, 2020, while its Kendall correlation is 0.760 after fast outbreak of Europe COVID-19 pandemic, increasing the 31.261% level. The Kendall correlation coefficient both IPE oil futures and Spain IBEX stock markets enhances from 0.244 before February 20, 2020 to 0.252 after February 20, 2020, enhancing the 3.279% level. The absolute Kendall correlation coefficient both IPE oil futures and Italy MIB (UK FTSE) stock markets reduces from 0.239 (−0.104) before February 20,
The fast outbreak of COVID-19 pandemic triggers the significant dependence ranges both IPE oil futures and stock markets in Europe after quick outbreak of the COVID-19 pandemic, which promotes their Kendall correlation between IPE oil futures and France (Spain, German) stock markets, and decreases the absolute Kendall correlation between IPE oil futures and Italy (UK) stock markets after fast outbreak of COVID-19 pandemic.
However, the Kendall correlations both WTI oil futures and specific stock markets in America keep different ranges using R-vine copula function, compared with oil-stock dependence range in Europe in Table 8. The Kendall correlation coefficient both WTI oil futures and US NDAQ stock markets decreases from 0.245 before March 23, 2020 to 0.125 before June 30, 2020, reducing the 48.980% level, and then it increases from 0.125 to 0.241 after June 30, 2020, raising the 92.800% level. The Kendall correlation both WTI oil and Brazil IBOV (Mexico MXX) stock markets drops down from 0.146 (0.055) to −0.045 (−0.021), descending the 30.822% (38.182%) level, and enhances from −0.045 (−0.021) to 0.184 (0.209). Moreover, the Kendall correlation both WTI oil and Canada TSX stock markets increases from 0.056 to 0.106, raising the 89.286% level, and finally amplies from 0.106 to 0.287, enlarging the 170.755% level. Those statistical results demonstrate that rapid outbreak of COVID-19 pandemic in America triggers the twice dependence structure break both WTI oil and specific stock markets in America, and induces more significant dependence ranges after twice structure break point. The risk spillover both WTI oil and US (Brazil and Mexico) stock markets first weakens quickly after first structure break point and then amplies fast after second structure break point, while the risk spillover both WTI oil and (Canada) stock markets also strengthens quickly after first and second structure break point.

5.5. Robustness test of dependence structure break

In order to further investigate that the COVID-19 epidemic event trigger the dependence structure breaks in the crude oil and stock markets in Europe and America, this article tends to use C-vine Copula model to provide their robustness test of their dependence structure, and their dynamics \( \lambda_1 \) value trends and their dependence structure breaks are shown in Figs. 9 and 10. In Europe, the maximum \( \lambda_1 \) value is 75.160 simulated by C-vine copula model, the probability is less than 1% on February 20, 2020, those results demonstrate the COVID-19 epidemic event triggers the dependence structure break between IPE oil and European stock markets on February 20, 2020, its dependence structure break have good robustness using C-vine copula and R-vine copula. In America, the first maximum \( \lambda_1 \) value is 30.900 using C-vine copula function, its probability is less than 5% on March 23, 2020, the COVID-19 epidemic event triggers the first dependence structure break between WTI oil and American stock markets on March 23, 2020. The second maximum \( \lambda_2 \) value is 41.840 and its probability is less than 1% on June 30, 2020, the COVID-19 epidemic event yet triggers the second dependence structure break between WTI oil and American stock markets on June 30, 2020, two oil-stock dependence structure breaks induced by the COVID-19 epidemic event have good robustness in America using C-vine copula and R-vine copula functions.

This section further evaluates the Kendall correlation coefficients in Europe and America using C-vine copula function, and their results are shown in Table 9. In Europe, their Kendall correlation coefficients both CAC, IBEX DAX stock indices and IBOV oil futures price increase 31.261%, 37.143 and 6.294 respectively, while their absolute Kendall correlation coefficient both MIB (FTSE) stock indices and IBOV oil futures price decreases 19.247% (24.038%) respectively during the dependence structure break phase, their Kendall correlation coefficients cater good robustness test after oil-stock dependence structure break point using C-vine copula function. In America, compared with before March 23, 2020, their absolute Kendall correlation coefficients both NDAQ, IBOV, MXX stock indices and WTI oil futures price reduce 48.980%, 5.357% and 89.041% respectively during the first dependence structure break phase, their Kendall correlation coefficients increases 103.200%, 228.302% and 962.500% respectively during the second dependence structure break, the Kendall correlation coefficient both TSX stock indices and WTI oil futures price increases 96.364% during the first dependence structure break and increases 176.852% during the second dependence structure break. Their Kendall correlation coefficients in America have good robustness during the first and second dependence structure breaks using R-vine and C-vine copula functions.

6. Conclusions

As an international concerned public health emergence, COVID-19 pandemic has produced significant market shocks on international crude oil and global stock markets. This article selects the severe investigate that COVID-19 pandemic event corrects the dependence structure between international crude oil futures and specific stock markets in Europe and America using ARMA-GARCH and R-vine copula methods, and examines the robustness test using C-vine copula function.

Our empirical results demonstrate that the returns of international oil futures prices and selected stock indices in Europe and America exhibit significant ARCH and GARCH effects and volatility clustering effects in the period considered, which has similar results with Bein (2017), Lu et al. (2017) and Zhang and Ma (2019). The estimated results of pair-vine copula models confirm that France and Germany (UK, Italy) stock markets exhibit asymmetric dependence structures and risk contagions, and IPE crude oil futures and France (Spain) stock markets yet indicate symmetric dependence structure in Europe. However, Reboredo and Ugolini (2016) find that oil and stock markets in the Central and Eastern Europe have significant and asymmetric dependence structure. The US and Brazil (Canada) stock markets reveal significant asymmetric dependence structure in America, and WTI crude oil futures and the US stock markets show significant asymmetric dependence structures with an increase of COVID-19 pandemic, while Reboredo and Ugolini (2016), Ji et al. (2020a,b) and Cui et al. (2021) find that oil and stock market exhibit significant asymmetric dependence structure after financial crisis. The rapid outbreak of COVID-19 pandemic significantly triggers the dependence structure break between international crude oil and stock markets in America using C-vine copula and R-vine copula functions.
oil and European (American) stock markets on February 20, 2020 (March 23 and June 30, 2020). In Europe, the time-varying Kendall correlation both IPE oil and France (UK) stock markets display an increase trend, while the dynamic Kendall correlation both IPE oil and German (Italy and Spain) stock markets reveal significant market fluctuations after fast outbreak of European COVID-19 pandemic. However, Aloui et al. (2013) finds that oil and stock markets in Europe have time-varying dependence structure break after financial crisis. In America, the dynamic Kendall correlations both WTI oil and the US (Brazil) stock markets quickly drop down and then fluctuate after March 23, 2020, while the time-varying Kendall correlations both WTI oil and Canada (Mexico) stock markets show lower market shocks. In Europe, Kendall correlation measures demonstrate that rapid outbreaks of COVID-19 pandemic enlarge significantly the dependence risks between IPE oil and France (Spain and German) stock markets, and reduce significantly the dependence risks between IPE oil and UK (Italy) stock markets, and then demonstrate their dependence structure break has good robustness using C-vine copula function. In America, the fast outbreaks of COVID-19 pandemic descend significantly the dependence risks between WTI oil and US (Brazil and Mexico) stock markets in the period from March 23, 2020 to June 30, 2020, and then quickly boost their dependence risks after June 30, 2020, while amplify the dependence risk between WTI oil and Canada stock markets after first and second structure break points, which have good robustness using C-vine copula function. However, Zhu et al. (2016) and Yu et al. (2020) find that oil and stock markets in USA and China have significant dynamic dependence structure breaks after financial crisis.

Our findings provide new implications for policy-makers and investors after outbreak of public COVID-19 pandemic event. First, government policymakers pay much attention that extreme public COVID-19 pandemic changes induced international crude oil futures and stock markets produce significant time-varying risk contagion, which implies sudden increase of COVID-19 pandemic exacerbates abrupt their price movements. Policy-makers should control smooth changes in COVID-19 pandemic amount and provide steady and positive economic policy supports. Our evidences demonstrate that market investors...
should pay much attention to extreme asymmetric and time-varying co-movement and dynamic dependence structure break in international energy and stock markets after the onset of increased COVID-19 pandemic amount. Market investors should take into account extreme dependence structure break and optimize risk management portfolios and their investment choices. Our study has some limitations in the uncertainties in economic activities and economic policy. Fast increased COVID-19 pandemic events also produce greater uncertainty of economic activities, blocked international trade and global supply chain, greater decline of social consumption and economic output etc. Greater uncertainty economic activities and economic policy may induce extreme market shocks in energy and stock markets, those time-varying influences provide future studies for many scholars. Future studies can consider the volatility asymmetry and risk contagion between stock and energy commodity markets induced by sudden public events, such as Russian Ukrainian War, extreme climate change and black swan events etc. The equity-commodity asymmetric dependence structure exhibits variant dynamic directionality and Variable structural breakpoints in extreme down movements in different equity and commodity markets. Those extreme public events would mask potential heterogeneity between stock market and energy commodity markets. For example, extreme climate changes may induce greater market volatility asymmetry and exhibit potential heterogeneity in fossil energy commodity and climate-related stock sectors, such as heavy-industry sectors, energy sectors and clean energy sectors etc.

CRediT authorship contribution statement

Kai Chang: Research design and study method, Writing – original draft, Revised the manuscript. Sheng Ze Li: Data curation. Empirical results of the whole manuscript.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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