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Dependence structure of the US dollar index and crude oil prices: a regime-switching copula approach

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Abstract

Purpose – In recent years, the world has faced a series of crises, including COVID-19 and the Russia–Ukraine conflict. These events have significantly changed the dynamics of the financial commodity markets. Considering the significance of the US dollar and crude oil as essential financial instruments, it is crucial to analyze the changes in their interactions to understand the implications for economic growth. This study aims to investigate the relationship between the US dollar index and crude oil prices from 2017 to 2023.

Design/methodology/approach – A regime-switching copula model was used in this study. Although each global crisis can introduce new changes to these relationships, the general static and time-varying copulas may more accurately represent the dynamics of these connections. Both the time-varying and static copulas exhibit insensitivity to anomalies. By integrating the strengths of copula and Markov regime-switching (MRS) models, the MRS copula model serves as a dynamic mixed copula model. It can incorporate multiple copulas to address various research questions.

Findings – The empirical findings indicate that the Gaussian copula model with regime switching is more effective in fitting the experimental data. The results of the model fitting revealed two distinct dependency structures: one exhibited a positive correlation, and the other demonstrated a negative correlation. This finding contrasts with the prevailing literature, which typically indicates a negative correlation between the US dollar index and crude oil prices. Furthermore, there is a reciprocal relationship between these two dependency structures, which exhibits Markovian characteristics.

Research limitations/implications – This study has several limitations. To improve the empirical utility of the model, some researchers have refined the copula within the MRS framework, while others have enhanced its applicability by incorporating additional variables. This opens up potential avenues for further investigations.

Practical implications – The results have significant implications for managers. Furthermore, compared to the standard model, the regime-switching copula model is more responsive and sensitive. In light of the recent

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trend of dollarization, policymakers and central banks must reconsider their monetary policies for conducting international business, diversify their foreign-exchange holdings and enhance their risk aversion.

Originality/value – The originality of this paper lies in the data it provides to support the conclusion that the MRS copula model outperforms the basic copula model, thereby facilitating generalization of the MRS copula model. These findings contribute to the advancement of knowledge among scholars regarding the changes in the interconnection structure across financial markets resulting from crises. This implies the ability to make more informed decisions for both investors and governments.

Keywords Dependence structure, Crude oil prices, Markov regime-switching copula, US dollar index, COVID-19, Russian–Ukrainian war

Paper type Research paper

1. Introduction

Since the US dollar became the primary medium of exchange for international commerce in the 1970s, a significant correlation has emerged between crude oil, one of the most essential commodities in the global economy and the US dollar. The interdependence of these elements remains a major concern in economics. Liquid fuel, primarily derived from crude oil, has consistently been the world's most widely used primary energy source for decades. Owing to the critical role of liquid fuels, crude oil prices serve as vital indicators of the development of the global energy market. Fluctuations in crude oil prices significantly impact global economic activities, as energy commodities derived from crude oil increasingly shape economic behavior (Jones *et al.*, 2004; Hamilton, 2009a, 2009b; He *et al.*, 2010; Pircalabu and Benth, 2017; Badwan and Al-Qubbaj, 2024; Bhattacherjee *et al.*, 2025).

Within the international monetary system, as noted by Goldberg and Tille (2008), Gopinath (2015) and Gopinath *et al.* (2020), the US dollar serves as the central currency and is responsible for transmitting, moderating and controlling price fluctuations across the world's markets and economy. Variations in the value of the US dollar have a direct effect on international commerce, which, in turn, affects the global economy (Tarr, 2010; Avdjiev *et al.*, 2019; Zhang and Lin, 2019; Tekin and Badwan, 2024). However, individual exchange rates do not accurately reflect the true value of the US dollar within a broader macroeconomic context. The US dollar index (USDX) is a quantitative measure that assesses the value of the US dollar by combining its exchange rates with a basket of foreign currencies in the global market. Consequently, the USDX is a more appropriate proxy in empirical financial studies.

The USDX and crude oil prices have been closely linked since the establishment of the US dollar oil system was established in the 1970s, when the US dollar was designated as the exclusive currency for oil transactions. As crude oil is priced globally in US dollars, fluctuations in the USDX are often seen as the primary catalyst of changes in crude oil prices (Zhang *et al.*, 2008). The relationship between the US dollar and crude oil has been strengthened. The analysis of their interdependence is a significant topic in the field of economics.

Initially, researchers tended to examine this relationship from an empirical perspective. For example, Barsky and Kilian (2002) analyzed and assessed several well-known economic justifications for rising oil prices. Their findings suggest that oil market volatility may not significantly impact the functioning of the US economy, contrary to prevailing assumptions. However, when considering their interdependence, the empirical analysis approach has inherent limitations and may fail to yield accurate and comprehensive results. Consequently, an increasing number of scholars are shifting toward analyzing relationships from a modeling perspective. For instance, Liao *et al.* (2018) used a DCC-GARCH model to investigate the time-varying relationship between crude oil prices and the USDX and proposed the existence of significant mediating factors that contribute to the temporal variability of this association.

Some academics argue that the dependency structure among financial commodities has changed because of the ongoing global crises. A compelling question arises:

Q1. Have there been any changes in the relationship between the US dollar and crude oil, which are two essential financial assets?

Further research is required to address this question. Nevertheless, classical time-series models have limitations in capturing the intricate interdependence networks among financial data. For example, nonlinear and asymmetric structures are challenging for traditional models to adequately represent. Using copula models offers a more effective approach to address these issues. However, during crises, the standard copula model may lack sensitivity. According to Okimoto (2008), the basic copula model is less effective than the Markov regime-switching (MRS) copula model, which was first proposed by Hamilton (1989).

This study aimed to explore the relationship between the USDX and crude oil prices using a MRS copula model. The MRS copula model enhances the sensitivity to variations in variable interactions while maintaining the flexibility of a standard copula. This combination allows for a more comprehensive investigation of the interactions between variables, thereby improving the accuracy and depth of the analysis of the interdependence structure. Currently, there is a lack of research on the application of the MRS copula model to analyze the evolving linkages between financial markets.

In this study, we present a regime-switching MRS copula model to elucidate crisis-induced shifts in the connectivity structure across financial markets. The regime-switching component is crucial for distinguishing between scenarios with similar prices and those with nonidentical pricing. The MRS copula model serves as a filter to eliminate serial dependency in the conditional means and variances. Copula models facilitate analysis by allowing the independent consideration of marginal models for day-ahead prices, regardless of the dependency structure. Furthermore, copulas provide a more comprehensive understanding of the dependency structure in instances where prices diverge, as well as a seamless transition to more realistic distributional assumptions for residuals.

Our study contributes to the existing literature and advances the current field of study. Furthermore, this study presents an original case study on the relationship between crude oil and the US dollar. According to our findings, this relationship is no longer fundamentally negative in the long run. This discovery aligns with the ongoing global trend of de-dollarization and the long-term movement toward economic diversification in the region. National leaders whose economies heavily depend on the US dollar and investors with a strong preference for it should be aware of this shift in the relationship. Finally, our work provides evidence that the MRS copula model outperforms the traditional copula model, making the MRS copula model more applicable across various contexts. This study encourages scholars to gain a deeper understanding of the changes brought about by the financial crisis in the interconnectedness of financial markets. Consequently, it aids in the development of more accurate assessments, which have significant implications for investors and decision-makers.

The remainder of this paper is organized as follows. A review of the current literature is presented in Section 2. The data statistics are presented in Section 3. Section 4 outlines the proposed approach. Section 5 presents the analysis and empirical results. Section 6 presents the conclusion and implications.

2. Brief literature review

Owing to several interrelated factors, the price of crude oil has fluctuated significantly in the international market in recent years, increasing market risk and raising considerable doubts about crude oil price forecasts. Consequently, academic researchers, policymakers and oil market investors must accurately analyze and forecast oil prices (Zhang and Wei, 2010). As the world's largest developing nation and a major consumer of energy, China's reliance on imported crude oil is growing, and fluctuations in global oil prices will affect the country's overall economic growth. Therefore, investigating oil price fluctuations and their underlying drivers remains a significant and complex issue.

The relationship between crude oil prices and their influencing factors has been the focus of an increasing body of literature over the past several decades. Key contributors to the significant fluctuations in crude oil prices include the economic crises, supply and demand dynamics, inventory levels, OPEC activities, the exchange rate of the US dollar, military conflicts, severe weather conditions, speculative trading, psychological expectations and other variables (Bubaš, 1999; Kaufmann *et al.*, 2004; Adams and Shachmurove, 2008; Kilian, 2009; Kaufmann and Ullman, 2009; Miao *et al.*, 2017; Anjum, 2019; Tiwari *et al.*, 2019; Badwan, 2024). Although there is a strong correlation between the US dollar and crude oil prices, it is important to note that this relationship is not always straightforward or easily comprehensible (Amano and Van Norden, 1998; Yousefi and Wirjanto, 2004).

The nonstationary nature of actual oil prices has been the primary driver of the nonstationary behavior of the dollar exchange rate since the post-Bretton Woods period. According to Chaudhuri and Daniel (1998), there is evidence that causation and cointegration exist between the two variables. Lizardo and Mollick (2010) projected variations in the US dollar's foreign exchange rate by using a currency model that incorporated an oil price factor. Long-term predictions of oil prices match the patterns currently observed in the market. Sadorsky (2000) also found a long-term association between the USDX and crude oil prices, indicating that these two variables have a stable and persistent link.

However, some academics assert that there is an inconsistent short- and long-term link between the US dollar and crude oil (see Indjehagopian *et al.*, 2000; Wang and Chueh, 2013; Sun *et al.*, 2017). Peng *et al.* (2021) explored the multiscale frequencies of the dynamic relationship between US currency and crude oil. The findings demonstrate that the long-term and general correlations between the US dollar and crude oil prices follow similar trends, with negative correlations in the low-frequency inherent mode functions being more robust and stable over a longer time horizon, while negative correlations in the high-frequency inherent mode operations are more fragile and exhibit time-varying aspects over a shorter time frame. This result suggests that while the long-term relationship between the US dollar and crude oil prices remains consistent, short-term fluctuations can lead to varying degrees of correlation. Understanding these dynamics is crucial for investors and policymakers as they navigate the complexities of the global market.

Basher *et al.* (2012) presented a structural vector autoregressive (VAR) model to investigate the relationship between oil prices, the US dollar exchange rate and emerging market stock prices. The findings show that short-term increases in oil prices harm stock prices and the dollar rate. Zhou *et al.* (2021) examined the relationship between the USDX and crude oil prices using a time-series network model. According to the study, as the USA loses its position as the world's economic leader, the inverse relationship between the USDX and high-frequency oil prices weakens.

Nonlinearity, fat tails, price spikes and elevated volatility are the main characteristics of financial data, and these issues frequently make it difficult for a single conventional time-series model to work effectively. Recently, the financial industry has extensively used a new class of models called copula functions, which have flexible and adaptable building techniques and are capable of accurately capturing nonlinearities and tail linkages.

Using the copula approach, Aloui *et al.* (2013) examined the conditional dependence structure between crude oil prices and the US dollar exchange rate. They fit the potential dependence structure of rising and falling market phases using various copula function models, including Archimedean and elliptic families. The study's findings reveal a strong symmetry in the dependency structure between the US dollar exchange rate and crude oil prices from 2000 to 2011, indicating that an increase in crude oil prices is correlated with a decline in the US currency. The analysis also indicated that the t-copula model best matched the data. Wu *et al.* (2012) used a dynamic copula model to analyze the relationship between the USDX and crude oil prices. The findings demonstrate that t-copula-based dynamic strategies are more economically efficient than static and other dynamic strategy models. The study also indicates a statistical significance for positive feedback trading activity in the oil market. Using the CARR and copula models, Pu and Guo (2017) investigated the correlation structure and link between crude oil prices and the USDX. The findings reveal that variation points and economic events are closely related to each other. Ji *et al.* (2019) explored the dynamic relationship between crude oil and US and Chinese currency rates using the time-varying copula approach. The findings indicate that the USDX and daily and weekly crude oil prices exhibit structural dependency breakpoints. A substantial negative connection with both upper and lower tail reliance is observed between crude oil prices and the USDX. Given that today's economic events are more complex and challenging than those of the past, more scholars are beginning to focus on how crises affect the US dollar and the crude oil reliance system.

Mo *et al.* (2018) examined the evolving relationships among crude oil, gold and the US dollar. They discovered that these markets are strongly dependent on each other in the long term and that there is a constant negative relationship between oil and the US dollar. After the crisis, positive nonlinear causation was observed between the US dollar and crude oil.

Using copula and DCC-MGARCH models, Sebai and Naoui (2015) examined the relationship between oil prices and the US dollar's exchange rate. According to their findings, currency rates and oil prices were unlinked before the crisis but interacted during the crisis. In 2018, Bedoui *et al.* (2018) used a GARCH model based on a layered copula to study the dependency structure of oil, gold and dollar prices. Their findings show that during a crisis, the three are more dependent on one another than they are independent of one another. After thoroughly analyzing the literature on crude oil and the US dollar, we found that the relationship between the two has become more complex due to global crisis events and economic booms. This circumstance is not properly addressed by the traditional research methodologies currently in use. For example, the US dollar and crude oil have a nonlinear connection, but typical time-series approaches primarily consider linear interactions.

Furthermore, cointegration techniques are insensitive to short-term fluctuations and focus primarily on the long-term relationship between them. While each global crisis can bring fresh changes to their relationship, static and time-varying copulas may better characterize these changes. However, both time-varying and static copulas are insensitive to anomalies. The MRS copula model combines the advantages of copula and MRS models to create a dynamic mixed-copula model.

Its great flexibility allows it to combine several copulas in response to various research challenges (Benth and Kettler, 2011; da Silva Filho *et al.*, 2012; Wang *et al.*, 2013; Avdulaj and Barunik, 2015; Luo *et al.*, 2015; Boubaker and Sghaier, 2016; Phadkantha *et al.*, 2019; Gong *et al.*, 2020; Rikhotso and Simo-Kengne, 2022). Gozgor *et al.* (2019) noted that the MRS copula outperforms traditional time-series analysis techniques in capturing tail-dependent, asymmetric and nonlinear properties among variables. Compared to the plain-vanilla copula, it is also more flexible.

Zhou *et al.* (2021) construct comovement threshold networks according to a distinct period's approach split by structural breakpoints using high-frequency oil prices, crude oil stocks and the USDX, following ensemble empirical mode decomposition. Their findings show that the negative relationship between the USDX and high-frequency oil prices becomes more apparent during periods of significant oil price volatility the comovement network of these three variables resembling a "small-world network." The inverse relationship between the USDX and high-frequency oil prices has gradually weakened. Meanwhile, the reverse relationship between stocks and high-frequency oil prices has grown increasingly significant as oil prices have returned to stable fluctuations, and the US's leadership role in the global economy has begun to wane.

Dai *et al.* (2021) determined the new industrial policy observatory (NIPO), a straightforward yet effective indicator of the oil price. They also presented fresh data demonstrating the strong out-of-sample forecasting potential of the USDX on oil prices. Furthermore, the authors demonstrate a positive relationship between NIPO and the USDX for oil price forecasting. This relationship is explained through the lens of economic transmission mechanisms and linear correlations. The application of multivariate forecasting techniques can significantly enhance the statistical and financial performance of models incorporating the USDX and NIPO. Specifically, the ability of the USDX and NIPO to predict oil market sentiment and inflation, respectively, contributes to the improved oil price forecast accuracy. These predictive capabilities can be further strengthened by using appropriate, nonlinear models.

Tuğba (2022) examined the dependency structure between the dollar rate and electricity index using the copula function. To evaluate the model fit, the study used the mean squared error (MSE), Akaike information criterion (AIC) and Bayesian information criterion (BIC). The results indicate that the Clayton copula was the most suitable in terms of MSE, whereas the Gumbel copula performed best according to the AIC and BIC criteria.

Donkor *et al.* (2022) examined the relationship between the volatility of currency rates and oil prices in a collection of oil-dependent countries before and during the global financial crisis of 2008–2009, as well as the associated causal patterns. We used weekly time-series data on oil prices and exchange rates for the precrisis years 2000–2007 and the postcrisis years 2010–2016. The Ghanaian cedi, Nigerian naira, Russian ruble, Indian rupee, South African rand and euro all have exchange rates denominated in US dollars. By creating bivariate VAR-GARCH and VAR-EGARCH models, we combined vector autoregressive with GARCH and EGARCH models to examine the volatility influences that exist between oil prices and exchange rates during both subsample periods. We also used the Toda–Yamamoto causality test to examine similar causality patterns. The empirical results of the study show a bidirectional and unidirectional relationship between oil price volatility and exchange rates for four of the six oil-dependent economies considered. Compared to the precrisis period, these findings were more frequent in the postcrisis period.

Gürsoy *et al.* (2022) examined how the US monetary policy uncertainty index affects the dollar index (XD). This study examined the relationship between the US MPU (USM) and XD. Using monthly data, we apply the Hatemi-j (2012) asymmetric causality test for the period from January 1986 to August 2020. The results of the empirical analysis show a robust, nonlinear causal relationship between XD and the MPU index. The overall result establishes that the XD and USM indices have a bidirectional, asymmetric nonlinear causal relationship that is both positive and negative. The results of the empirical investigation support crucial policy recommendations for those who formulate macroeconomic policies.

Research on bivariate or multivariate models of crude oil prices in the context of interconnected financial markets is scarce. Kiesel and Kusterman (2016) and Voss *et al.* (2017)

are two examples of scholars who use canonical models as a result of the increasing complexity of joint pricing dynamics, as noted earlier. Kiesel and Kusterman (2016) constructed closed-form pricing formulas for simple futures and options under market coupling and presented a canonical model based on Carmona *et al.* (2013). They also provide an empirical application using data from French and German markets. Voss *et al.* (2017) also use a canonical model and study the pricing of futures and transfer rights under different allocation regimes. They also conducted sensitivity studies and provided closed-form pricing algorithms.

However, as Kiesel and Kusterman (2016) noted, canonical models can be quite data-intensive and thus theoretically and empirically challenging, even if they are attractive in terms of their ability to adapt to changes in market structure, which occur quite frequently. The data inputs for Kiesel and Kusterman (2016) empirical study of Germany and France came from a variety of time series, including energy price data, data on installed transmission capacity, data on coal, gas and oil as proxies for marginal fuels, and data on the expected residual demand for both countries. However, our proposed model, which falls into the category of short-form models, is not nearly as data-intensive while still adhering to the institutional framework as the aforementioned models.

In the context of increasing global crude oil price fluctuations, studying short-term price fluctuations and the relationship between the USDX and its independent structure plays an important role. Additionally, the global dollar exchange rate with crude oil prices presents additional challenges.

Based on the literature review, the research gap can be summarized as the need for new data to strengthen the conclusion that the MRS copula model is superior to the basic copula model used in previous studies. This study is one of the first to use an MRS approach. The copula MRS approach addresses the problem of the study and achieves its main objective. Accordingly, our study contributes to the generalization of the MRS copula model. Finally, we need to overcome the shortcomings of econometrics and improve the characteristics of short-run crude oil price volatility and its influencing factors. Previous studies have not commonly examined oil prices after decomposition. Therefore, the current study fills this research gap by analyzing the joint relationship between crude oil prices and the USDX, as well as the main influencing factors (crude oil stocks and the USDX), from the perspective of complex networks. In addition to actual events, we examine the inherent relationship between crude oil prices and the USDX from 2017 to 2023.

3. Data, methodology and preliminary analysis

3.1 Data

Based on the hypothesis that global crises have the potential to alter the dynamics of financial commodities, we examined data on USDX and crude oil prices from 2017 to 2023, a period marked by an exceptionally high frequency of crises.

Figure 1 displays the time series of the closing prices of crude oil and the USDX from 2017 to 2023. Both positive and negative trends are present in USDX and crude oil prices. The logarithmic return series of the data is often used in real-world investigations. Logarithmic return refers to the closing price's logarithmic differential treatment, which can be expressed as follows:

$$r_t = \{Inp_t - Inp_{t-1}\} \tag{1}$$

Figure 2 displays the return series for crude oil and the USDX. In addition, Figure 3 illustrates intercorrelogram of the return series over time. Table 1 lists some statistical

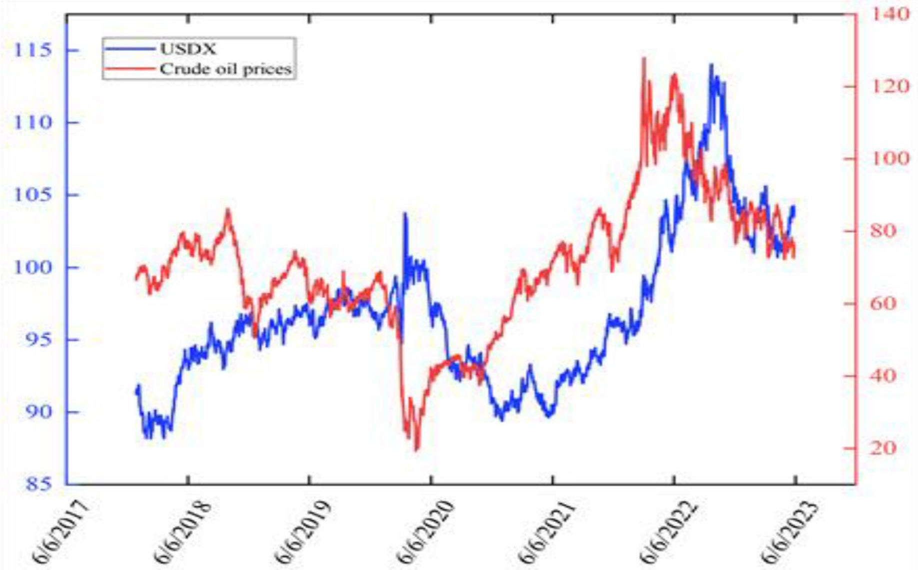

Figure 1. Time-series chart of closing prices
Source: Authors' own work

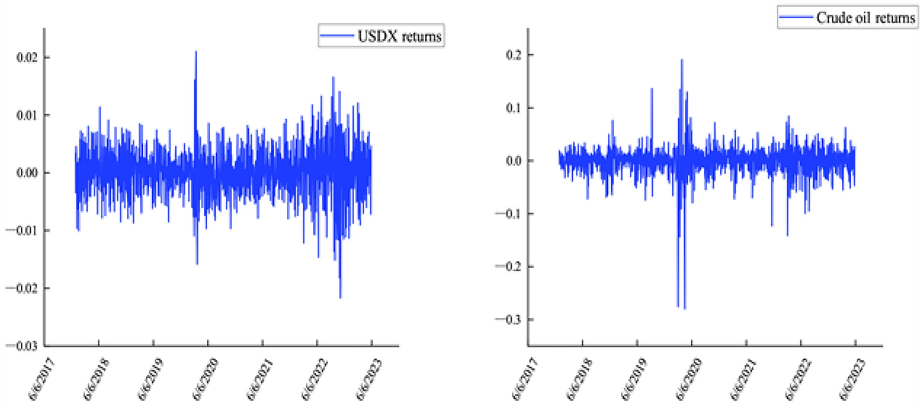

Figure 2. Series of USDX and crude oil returns
Source: Authors' own work

characteristics of the data used in the study. The findings of the table and chart demonstrate the close relationship between the volatility cycles of the USDX and crude oil, which generally move in opposite directions; that is, the dollar continues to rise while crude oil continues to decline. Around 2020, both became more unpredictable.

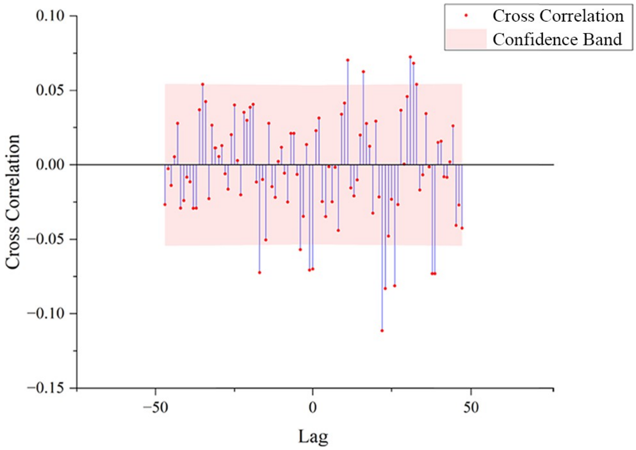

Figure 3. Intercorrelogram of the return series over time
Source: Authors' own work

Table 1. Descriptive statistics of return series

Variables	Crude oil	USDX
Mean	0.000093	0.000086
Median	0.002671	0.000001
Standard deviation	0.025613	0.005267
Minimum	−0.249807	−0.018955
Maximum	0.221148	0.027930
Variance	0.000816	0.000022
Kurtosis	18.270310	2.178340
Skewness	−1.246791	−0.011683

Source(s): Authors' own work

3.2 Methodology

The ability to independently study the marginal distribution and the dependence structure of the data is one of the benefits of the copula function; this reduces modeling complexity and enhances modeling accuracy. However, it also requires two steps in the process of building the copula model: first, creating a suitable marginal model for the data and then developing an appropriate copula model.

3.2.1 Models' specification. To construct the marginal model, this study will selects the best GARCH function from several traditional GARCH family models based on the features of the data. The GARCH family model is a traditional technique in financial time series research. Among the models in the GARCH family, the GARCH model is most frequently used. In general, it represented like this:

$$\left\{ \varepsilon_t = \sqrt{h_t v_t} \,\middle|\, h_t = \alpha_0 + \sum_{i=1}^{q} \alpha_i \varepsilon_{t-i}^2 + \sum_{i=1}^{p} \beta_i h_{t-i} \right\} \tag{2}$$

where

$$v_t \sim \boldsymbol{IID}(0,\,1);\ \alpha_0 > 0;\ \alpha_i \geq 0,\ i = 1,\ 2,\ 3,\ \ldots,\ q-1,\ \alpha_q > 0;\ \beta_i \geq 0,\ i = 1,\ 2,\ 3,\ \ldots,$$

$$p-1,\ \beta_p > 0;\ \sum_{i=1}^{q} \alpha_i + \sum_{i=1}^{p} \beta_i < 1$$

3.2.2 Markov Regime-Switching copula-models specification. The whole copula theory is based on Sklar's theorem. Let's say that the returns on the USDX and the price of crude oil are (*X*) and (*Y*), respectively. Sklar's theorem states that there is a copula function (C) such that:

$$H(x_1,\, x_2) = C\big(F_1(x_1)F_2(x_2)\big) \tag{3}$$

where $x_1 \epsilon X;\ x_2 \epsilon Y,$ H is the joint distribution of the marginal distributions $F_1;\ F_2$of X and Y. Formula 4 can also be written as follows:

$$C(u,\, v) = H\big(F_1^{-1}(v)F_2^{-1}(v)\big) \tag{4}$$

where $u = F_1(x_1);\ v = F_2(x_2);$ u and v follow a uniform distribution

The MRS copula developed in this study combines two static copulas, with the state variables fully controlling its dynamic features. The copula function varies in tandem with changes in the state variable. For most financial data variants, two-state Markov transition models are sufficient. We consider a two-state Markov process. A stochastic process is said to be Markovian when its conditional probability distribution of future states depends solely on its current state rather than on all previous states. This is how its transfer probability is expressed as follows:

$$p_{ij} = P(\theta_t = j | \theta_{t+1} = i);\ i, j = 0,\ 1$$

The transfer probability matrix for it is as follows:

$$P = \left\{ \begin{pmatrix} p_{00} & 1 - p_{00} \\ 1 - p_{11} & p_{11} \end{pmatrix} \right.$$

where p_{ij} is the transition probability from state i at time t to state j at time t + 1.

The additive nature of the copula function allows for the following formulation of the MRS copula model:

$$C_t = (u_t,\, v_t,\, ;\, \alpha,\ \beta,\ S_t) = S_t C_t^1(ut,\ vt; \alpha) + (1 - S_t)C_t^2(ut,\ vt;\ \beta) \tag{5}$$

The authors selected the appropriate copula from several options – including the Gumbel, Clayton, t- and Gaussian copulas – to create the MRS copula. Only the copula expression used for the final model is included here to conserve space. Jaworski *et al.* (2010) present all of the copulas used. The Gaussian copula is characterized by high symmetry and independence properties that is easy to understand. The distribution function of the binary Gaussian copula is expressed as follows:

$$C(u, v; \rho) = \left\{ \int_{-\infty}^{\mathit{\Phi}-1(u)} \int_{-\infty}^{\mathit{\Phi}-1(v)} \frac{1}{\sqrt[2\pi]{1-\rho^2}} \exp\left(\frac{-\left(r^2 + s^2 - 2\rho rs\right)}{2(1-\rho^2)} \right) drds \right\} \tag{6}$$

Its density function may be expressed as follows:

$$\begin{aligned} C(u, v; \rho) = \Bigg\{ & \frac{1}{\sqrt{1-\rho^2}} \exp\left(\frac{\mathit{\Phi}^{-1}(u^2) + \Phi^{-1}(v^2) - 2p\mathit{\Phi}^{-1}(u)\Phi^{-1}(v)}{2(1-\rho^2)} \right) \\ & \times exp\left(-\frac{\mathit{\Phi}^{-1}(u^2)\Phi^{-1}(v^2)}{2} \right) \Bigg\} \end{aligned} \tag{7}$$

3.2.3 Estimation of parameters. In this study, the authors continue by estimating the parameters of the MRS copula using maximum likelihood, which are the most widely used techniques for copula model parameter estimation. We can derive the expression of the log-likelihood function by taking the logarithm of both sides of equation (5).

$$\begin{aligned} \log h\,(x_{1t},\ x_{2t}|\Omega_{t-1};\ \theta) = {} & \log f_1(x_{1t}|\Omega_{t-1};\ \theta_1) + \log f_2(x_{2t}|\Omega_{t-1};\ \theta_2) \\ & + \ \log c\,(u_t, v_t|\Omega_{t-1}; \theta_c) \end{aligned} \tag{8}$$

where h is the joint density of X_{1t} and $X_{2t}; f_i$ is the marginal density of X_{it}; c is the density of copula, Ω_{t-1} the information set available at the end of time $t-1$, $u_t = F_1(x_{1t}),\ v_t = F_1(x_{2t})$.

This research uses a two-step approach to estimate the parameters of the MRS copula ARMA-GARCH model based on the copula function features. To be more precise, the first stage involves estimating the parameters of the marginal distribution and the second step involves estimating the parameters of the copula by substituting the calculated values of the marginal distributions. The initial step involves the estimation of the marginal densities' characteristics by:

$$\theta_1 = \arg\ max_{\theta 1} \sum_{t=1}^{T} \log f_1(x_{1t}|\Omega_{t-1}; \theta_1) \tag{9}$$

$$\theta_2 = \arg\ max_{\theta 2} \sum_{t=1}^{T} \log f_2(x_{2t}|\Omega_{t-1}; \theta_2) \tag{10}$$

The parameters of the copula are calculated in the second step by:

$$\theta_c = argmax_{\theta c} \sum_{t=1}^{T} \log c(F_1(x_1; \theta_1),\ F_2(x_2; \theta_2) \nmid \Omega_{t-1}; \theta_c) \tag{11}$$

Equation (5) can be combined to change the log c component of equation (8) in the following way:

$$c_t(u_t,\ v_t|\Omega_{t-1};\theta_c) = \mathbb{P}(S_t = 0|\Omega_{t-1}) \times c_t^1\left(u_t,\ v_t|S_t = 0,\ \Omega_{t-1};\ \theta_c^1\right) + \mathbb{P}(S_t = 1(\Omega_{t-1}) \times c_t^2\left(u_t,\ v_t|S_t = 1,\ \Omega_{t-1};\ \theta_c^2\right)) = \xi_{t|t-1}^{'}\eta_t \tag{12}$$

where $\mathbb{P}(S_t = 0)$ represents the probability that $S_t$is a 0 state at time t; c_t^i is the density function of the copula in different regimes at time $t(i = 1,\ 2)$; $\xi_{t|t-1} = \left\{\mathbb{P}(S_t = 0|\Omega_{t-1}),\ \mathbb{P}(S_t = 1|\Omega_{t-1})\right\},\ <\eta_t = \left\{c_t^1\left(u_t,\ v_t|S_t = 0,\ \Omega_{t-1};\ \theta_c^1\right),\ c_t^2\left(u_t,\ v_t|S_t = 1,\ \Omega_{t-1};\ \theta_c^2\right)\right\}$. According to Hamilton (1994), we may use Hamilton's filter proposed to calculate $\xi_{t|t-1}$for t = 1, …, T as follows:

$$\xi_{t|t} = \frac{\xi_{t|t-1}\odot\eta_t}{\xi_{t|t-1}^{'}\eta_t} \tag{13}$$

$$\xi_{t+1|t} = P\xi_{t|t} \tag{14}$$

where element-by-element multiplication is indicated by the symbol ȯ. Next, we use equations (12)–(14) to maximize equation (11). Then, we may obtain an even more accurate gauge of the latent state variable by using these conditional likelihoods. To compute the smoothed probabilities $\xi_{t|T}$, we may iterate backwards from T to 1 starting with $\xi_{T|T}$. We can do this by iterating on:

$$\xi_{t|T} = \xi_{t|t}\odot\left[P^{'\left(\xi_{t+1|T}(\div)\xi_{t+1|t}\right)}\right] \tag{15}$$

where the sign $(\div)$ denotes element by element division.

3.2.4 Kendall's rank correlation coefficient. If $(x_1 - x_2)(y_1 - y_2) > 0$ for two random observations $(x_1,\ y_1)$ and $(x_2,\ y_2)$ of random variables $(X,\ Y)$, then $(x_1,\ y_1)$ and $(x_2,\ y_2)$ are considered consistent. It is argued that $(x_1,\ y_1)$ and $(x_2,\ y_2)$ are inconsistent if $(x_1 - x_2)(y_1 - y_2) < 0$. Sign combined $(x_1 - x_2)$. We cite Hollander *et al.* (2013) and Lehmann and D'Abrera (1975) for their definition of Kendall's rank correlation coefficient, a consistency correlation metric, and provide the following deformation:

$$\tau = \mathbb{P}\left\{(x_1 - x_2)(y_1 - y_2) > 0\right\} - \mathbb{P}\left\{(x_1 - x_2)(y_1 - y_2) < 0\right\} \tag{16}$$

It may be acquired additionally:

$$\tau = 2\mathbb{P}\left\{(x_1 - x_2)(y_1 - y_2) > 0\right\} - 1 \tag{17}$$

when $\tau \in (0,1]$, X and Y change in the same way and are positively correlated; when $\tau \in [-1,\ 0]$, X and Y change in the opposite way and are negatively correlated; and when $\tau = 0$, it is impossible to determine whether X and Y are correlated. These findings are based on the measurement of the random variables X and Y with τ.

4. Findings and discussion

4.1 Findings for marginal models

The range of p, q in ARIMA (p, q) between (0,3) is specified in this work, and the best order is chosen using the AIC information criteria. ARIMA (0,1) is the final mean component of returns for the USDX, while ARIMA (2,3) is the mean portion of returns for the price of crude oil. Next, based on the data in Table 1, we take into account three innovation distributions (skewed normal, student's t and skewed student's t distributions), five GARCH family models (GARCH, EGARCH, IGARCH, GJR-GARCH and APARCH), and the GARCH model that was not mentioned in Subsection 4.1.

Following this, choose the best marginal model from the options by following these procedures. First, the model with the lowest AIC values is selected to move on to the second phase based on the AIC information criterion. Second, these models' autocorrelation and heteroskedasticity were evaluated. Tests must be run for this evaluation, notably the weighted Ljung–Box test and the weighted ARCH-LM test on the residuals. Weighted Ljung–Box and weighted ARCH-LM tests are proposed by Fisher and Gallagher (2012) as an alternative to the Ljung–Box and ARCH-LM tests.

These tests provide a more comprehensive explanation of the distribution of the median values' statistics in the estimated model. Third, the Kolmogorov–Smirnov test is used to confirm that the probabilistic integral converted sequences obey an independent uniform standard distribution. This is done by applying a probability integral transformation to the residuals of the models that pass the test.

The marginal model that passes the tests is deemed ideal if every test that is run produces good results. Nevertheless, the procedure goes back to the first stage and starts over if the tests in the second or third phase fail. The most suitable model will be chosen thanks to this iterative process. The margin model's estimation results are presented in Tables 2–3. The authors leave out in the report the estimated results for the GARCH and ARIMA coefficients to conserve space. The authors are willing to provide these findings upon request. At some point, the student's t distribution. For the USDX returns, the

Table 2. Findings of the marginal estimation of models for USDX returns

	AIC	WLB test	WLM test	KS test
Skewed t distribution				
GARCH (1,1)	−7.418	0.853	0.452	1.000
EGARCH (1,1)	−7.710	0.862	0.252	1.000
IGARCH (1,1)	−7.507	0.818	0.472	1.000
GJR-GARCH (1,1)	−7.829	0.873	0.495	1.000
APARCH (1,1)	−7.528	0.862	0.590	1.000
Skewed normal distribution				
GARCH (1,1)	−7.097	0.881	0.422	1.000
EGARCH (1,1)	−7.404	0.875	0.289	1.000
IGARCH (1,1)	−7.655	0.886	0.483	1.000
GJR-GARCH (1,1)	−7.379	0.885	0.479	1.000
APARCH (1,1)	−7.527	0.896	0.552	1.000
Student's t distribution				
GARCH (1,1)	−7.188	0.873	0.485	1.000
EGARCH (1,1)	−7.793	0.862	0.206	1.000
IGARCH (1,1)	−7.670	0.894	0.383	1.000
GJR-GARCH (1,1)	−7.626	0.879	0.432	1.000
APARCH (1,1)	−7.226	0.887	0.789	1.000

Note(s): The weighted Ljung–Box test is known as the WLB test, while the weighted LM test is known as the WLM test
Source(s): Authors' own work

Table 3. Findings of the skew student-t distribution marginal model estimation for profits on crude oil

	AIC	WLB test	WLM test	KS test
Skewed t distribution				
GARCH (1,1)	−3.799	0.589	0.311	1.000
EGARCH (1,1)	−3.934	0.796	0.663	1.000
IGARCH (1,1)	−3.694	0.448	0.725	1.000
GJR-GARCH (1,1)	−3.904	0.974	0.642	1.000
APARCH (1,1)	−3.590	0.997	0.333	1.000
Skewed normal distribution				
GARCH (1,1)	−3.662	0.981	0.686	1.000
EGARCH (1,1)	−3.893	0.893	0.588	1.000
IGARCH (1,1)	−3.499	0.985	0.626	1.000
GJR-GARCH (1,1)	−3.892	0.997	0.673	1.000
APARCH (1,1)	−3.971	0.658	0.391	1.000
Student's t distribution				
GARCH (1,1)	−3.977	0.965	0.689	1.000
EGARCH (1,1)	−3.794	0.944	0.594	1.000
IGARCH (1,1)	−3.752	0.921	0.679	1.000
GJR-GARCH (1,1)	−3.980	0.998	0.592	1.000
APARCH (1,1)	−3.743	0.984	0.378	1.000

Source(s): Authors' own work

ARMA (0,1)–GARCH (1,1) margin model is chosen. Lopsided the t distribution of students, the returns on crude oil prices are attributed to the ARMA (2,3)–APARCH (1,1) margin model.

4.2 Markov regime-switching copula models findings

The observations derived from the marginal models are then used to model the MRS copula. In this study, we build the MRS copula model by doing the following: Initially, 16 distinct MRS copula models were created, including the Gaussian − Gaussian copula, Gaussian − t copula, Gaussian – Clayton copula, Gaussian – Gumbel copula, t – Gaussian copula, t – t copula, t – Clayton copula, t – Gumbel copula, Clayton – Gaussian copula, Clayton – t copula, Clayton – Gumbel copula, Gumbel – Gaussian copula, Gumbel – t copula, Gumbel– Clayton copula and Gumbel – Gumbel copula. The importance of the computed parameters of the different models is then examined. Ultimately, the best model is chosen based on the AIC information criterion among the models that pass the significance test.

The results of the parameter significance tests, as well as the AIC and BIC values, are presented in Table 4. The dependence structure between the USDX and the price of crude oil is analyzed using the Gaussian-Gaussian MRS copula model, following the modeling steps mentioned above. The estimated results of the Gaussian-Gaussian MRS copula model are presented in Table 5 and Figure 4.

The correlation between the two variables connected by the copula is reflected by the copula's correlation parameter, θ, as shown in Table 5. The Kendall coefficient is denoted by τ. The likelihood of many regimes emerging is depicted in Figure 4, where the positively correlated regime is referred to as the severe regime and the negatively correlated regime as the quiet regime. The findings indicate that, in general, the calm regime has a larger likelihood of formation than the extreme regime; nevertheless, before and following certain events, the extreme regime's probability of emergence is higher than the calm regime's.

Table 4. Analysis and decision-making regarding MRS copula models

Copula	θ	Dof	Copula	θ	Dof	AIC
Gaussian	0.642*** (0.000)	–	Gaussian	−0.376*** (0.000)	–	−63.481
Gaussian	0.931*** (0.000)	–	*t*	−0.112* (0.044)	5.217** (0.015)	−60.753
Gaussian	−0.367*** (0.000)	–	Clayton	0.647* (0.025)	–	−58.934
Gaussian	−0.468*** (0.000)	–	Gumbel	1.406*** (0.000)	–	−55.493
t	−0.007 (0.675)	3.217** (0.016)	Gaussian	−0.212** (0.009)	–	−72.419
t	0.036 (0.612)	3.519* (0.018)	*t*	−0.204** (0.011)	16.208 (0.286)	−75.491
t	−0.181* (0.018)	5.873* (0.033)	Clayton	0.851 (0.084)	–	−65.271
t	−0.137* (0.042)	4.972** (0.011)	Gumbel	9.135 (0.291)	–	−61.695
Clayton	0.673* (0.022)	–	Gaussian	−0.395*** (0.000)	–	−59.787
Clayton	0.876 (0.084)	–	*t*	−0.178* (0.019)	6.082* (0.037)	−66.442
Clayton	0.826 (0.189)	–	Clayton	0.015 (0.644)	–	9.621
Clayton	0.836 (0.163)	–	Gumbel	1.256*** (0.000)	–	8.945
Gumbel	1.343*** (0.000)	–	Gaussian	−0.484*** (0.000)	–	−52.734
Gumbel	9.205 (0.276)	–	*t*	−0.106* (0.038)	5.142** (0.015)	−57.962
Gumbel	1.389*** (0.000)	–	Clayton	0.018 (0.693)	–	8.204
Gumbel	1.412** (0.003)	–	Gumbel	1.203*** (0.000)	–	9.798

Note(s): The significance levels are indicated by *at the 5% level, **at the 1% level and ***at the 0.1% level. The *p*-values are enclosed in parentheses
Source(s): Authors' own work

Table 5. Findings from the ideal MRS copula

Copula	θ	T	Copula	θ	τ
Gaussian	0.625	0.446	Gaussian	−0.378	−0.211

Source(s): Authors' own work

4.3 Analysis of the dependence structure

There is now a consensus that a static or time-varying negative correlation generally exists between the USDX and crude oil prices, primarily because the US dollar has traditionally served as the official currency for international crude oil trade. However, the findings of this study reveal the presence of two distinct dependency structures – one positive and one negative – between the USDX and crude oil prices. These dependency patterns are dynamic and subject to change over time.

The results of this study are straightforward and accessible. While the US dollar remains the officially recognized medium for crude oil transactions in global trade, the emergence of a more diversified currency system has led to the use of alternative currencies in oil settlements. Notably, at the 2022 Gulf Cooperation Council (GCC) conference, China and the GCC signed an agreement to conduct oil transactions in yuan. This development poses a significant challenge to the historically strong link between the US dollar and crude oil.

Moreover, the US Federal Reserve's aggressive interest-rate hikes have had a dual impact: they have temporarily reinforced the negative correlation between the USDX and crude oil prices, while simultaneously accelerating the global shift toward de-dollarization. Consequently, while such interest rate increases can momentarily stabilize the negative

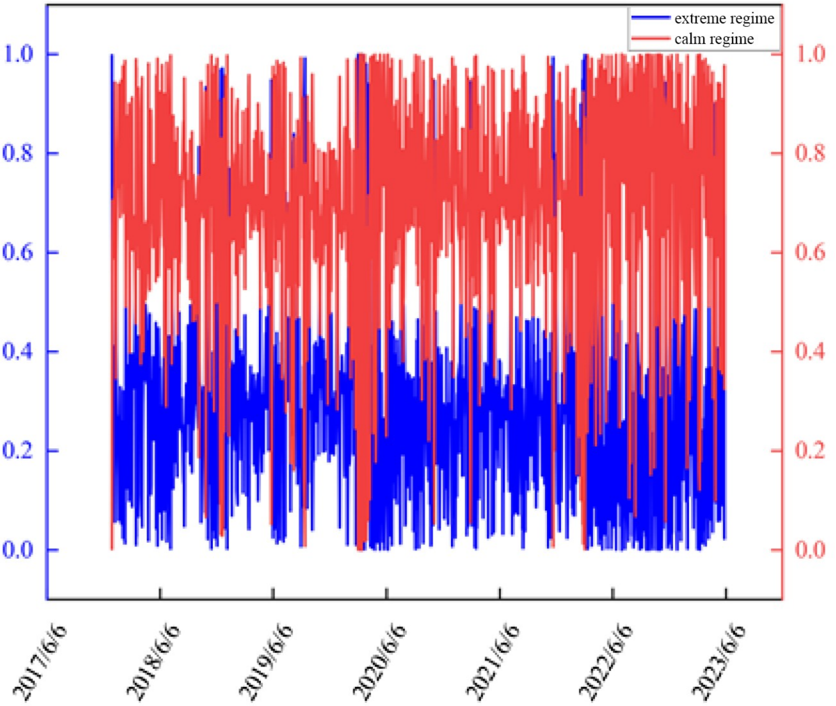

Figure 4. Probability of regime change from 2017 to 2023
Source: Authors' own work

correlation between the two, they may also contribute to the long-term emergence of new dependency structures.

Geopolitical risks affecting oil-exporting countries, such as the Russia–Ukraine conflict, Iran's nuclear program and the Israeli-Palestinian conflict (also referred to as the Israeli war on Palestine), have directly impacted crude oil production and exports, causing international price volatility and associated challenges. Furthermore, the USA became the world's leading oil exporter in 2018, surpassing China, which remains the largest oil importer.

The trade war between the two nations from 2018 to 2020 significantly affected both countries' economic growth and encouraged Middle Eastern and North African nations to diversify their dependencies away from the US dollar and crude oil. Finally, the ongoing global economic repercussions of the COVID-19 pandemic have further accelerated changes in the relationship between the USDX and crude oil prices.

5. Conclusion

This investigation uses an MRS copula model to examine the dependency structure between USDX and crude oil prices from 2017 to 2023. The findings demonstrate a dynamic dependency structure between USDX and crude oil prices during this period, with alternating positive and negative correlations. This switching mechanism is Markovian. According to Ji *et al.* (2019), a tail dependency existed between the USDX and crude oil prices from 2011 to 2017. However, the empirical findings presented in this research demonstrate that there is tail independence between the USDX and crude oil prices over the 2017–2023 timeframe. However, crude oil is not a safe-haven investment for US dollars.

This implies a greater likelihood of a positive link between the USDX and crude oil prices during a crisis than a negative one. Despite some prior experience suggesting that both gold and crude oil may be used as safe-haven assets, the results of this study show that crude oil cannot be a haven investment for the US dollar in times of crisis.

This study has important implications for investors and regulators. Policymakers also have much to learn from the findings. In the new wave of de-dollarization, policymakers and central banks should reassess monetary policy for international trade, diversify their foreign exchange holdings and strengthen their risk aversion.

In unexpected (often short-term) scenarios, the MRS copula model fits the dependence structure of crude oil prices and the USDX well. However, it is not without its limitations. Some researchers have improved the copula within the MRS framework to increase the usefulness of the model, while others have extended its application by adding more study variables, see for example Gong *et al.* (2020), Liu *et al.* (2020) and Tiwari *et al.* (2020). This gives us some potential for future research directions. Throughout the study project, changes in the volatility of both the USDX and the price of crude oil should be monitored simultaneously. Large, frequent changes in the price of oil are accompanied by its small ups and downs.

The USDX has shown greater volatility at times of dramatic swings in oil prices. This characteristic was aptly demonstrated by the global financial crisis that began in 2008. We must pay undivided attention to the shift in the XD. The inverse relationship between inventories and high-frequency oil prices is more evident during a period of stable oil prices, especially after stable price fluctuations have resumed. Furthermore, the USDX's significance is progressively declining in tandem with the country's declining dominant position in the world economy. These comovement characteristics will be crucial to future research as we construct an autonomous framework to predict changes in the USDX and crude oil prices.

In addition to offering some references for identifying the primary factors influencing short-term fluctuations in crude oil prices, the basic copula model and the MRS copula model also help researchers study the crude oil market and international currency markets, particularly the US dollar adjustment policies, accordingly to deal with price fluctuations. Finally, it will be more useful to adjust the link between crude oil and the USDX by comprehending the prevailing factors and the factors in distinct periods.

The findings also have important implications for policymakers. They should diversify foreign exchange reserves, reevaluate monetary policy for international commerce and strengthen their risk resilience in the wake of the recent wave of de-dollarization. The MRS copula model effectively fits the dependency structure of crude oil prices and the USDX in unforeseen, frequently short-term scenarios.

Despite some historical evidence to the contrary, this article's findings demonstrate that crude oil is not a safe-haven investment for the US dollar during crises. These findings have significant implications for investors. However, it also has certain limitations. Some researchers have improved its applicability by adding more research variables, while others have improved its practicality by refining the copula within the MRS framework. Based on these results, future research and additional studies on risk management, risk contagion and risk prediction can be conducted. These studies will provide guidelines for future investigations.

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