Crude Oil Transportation Route Choices: A Connectivity Reliability-Based Approach

Abstract: The crucial nodes of maritime transportation routes, such as the Strait of Malacca and the Suez Canal, remain vulnerable to various risk events including political instability and military conflict, piracy and terrorism, and vessel incidents. Existing shipping route choice studies often consider transportation costs and environmental effects, but ignore the connectivity reliability of these straits and canals. In this paper, we develop a bi-objective programming model to determine maritime transportation routes for crude oil, taking both transportation costs and connectivity reliability into consideration. We propose a method to measure the connectivity reliability of straits and canals, which captures the dependence structure of risk events. We apply our model to evaluate Gwadar Port using data covering 1999 to 2021, which is being built to enhance the reliability of Chinese oil imports. We find that the Gwadar Port can substitute for the Lombok Strait only if its connectivity reliability can be improved by 2.4%. In order to fully exploit the strategic advantages of Gwadar Port in substituting for other key straits, its connectivity reliability must be improved by 12.2%. Given the varying dependence of risk events identified in our model, our findings provide rich managerial and policy implications for connectivity reliability improvement.

Key words: Connectivity reliability; Energy transportation; Shipping route choices; Maritime policy

1. Introduction

Crude oil is an important strategic resource for all countries, but it is unevenly distributed around the world. Maritime transportation is the primary transportation mode of oil distribution, conveying about 90% of the world's total crude oil trade (Clarksons Research, 2019). Recently, the Russia-Ukraine war has actually induced roaring oil prices, e.g., European Brent crude oil prices climbed to $122.71 per barrel in June 2022, which increase 65.44% from December 2021(EIA 2022). And the safety of maritime transportation of crude oil and supply security again attracts a lot of attention, which plays an essential role in economic activity and national security.

While access to crude oil provides the foundation of modern industrial economies, the traditional maritime transportation routes of this vital resource are exposed to a number of risks. The straits and canals so vital to maritime transportation are particularly vulnerable to risk events like piracy and maritime terrorism, vessel incidents, political instability and military conflict (Emmerson and Stevens 2012; Bailey and Wellesley 2017). A vessel grounding incident caused the blockade of the Suez Canal in 2021, while the Russia-Ukraine war threatens the safety and reliability of tankers sailing through the Strait of Bosporus. If certain straits or canals are disconnected because of risk events, this directly affects the security of the crude oil supply. When selecting routes for crude oil transportation, it is thus imperative to consider the connectivity reliability of key nodes on top of the transportation cost. Such an approach to route choice better ensures the transportation reliability of the commodity widely regarded as the lifeblood of the global economy.

In previous studies, transportation costs and environmental effects have been widely considered in the construction of route choice models for crude oil transportation (Yahyaoui et al. 2021; Yamashita et al. 2019; Atmayudha et al. 2021; Jia 2018; Siddiqui and Verma 2015). Connectivity reliability, meanwhile, remains as yet under-explored. Connectivity reliability broadly refers to the probability that straits and canals will remain connected to the transportation network when subjected to risk events. Notably, the risk events are interrelated by nature (Emmerson and Stevens 2012; Li et al. 2023). The Russia-Ukraine war induces political instability in that region, and threatens the crude oil transportation safety and reliability; in the meanwhile, because of the sanctions against Russia, some old tankers have been purchased by "unknown" buyers to transport crude oil exported by the sanctioned countries, this is also likely to increase the probability of vessel incidents and reduce connectivity reliability (Umar et al. 2022). Piracy is also related to the political instability of a region; and heavy weather will restrict pirates from using their small, high-speed boats to attack ships. From this set of factors, researchers have concluded that most piracy will occur in an environment with milder wind and wave conditions (Jiang and Lu 2020, Liu et al. 2023). The dependence structure between these risk events is one of the most overlooked problems in an investigation of reliability, and an ignorance of the dependent relationships can produce faulty estimations.

The main contributions of this paper are threefold. First, it is a preliminary attempt to consider not just transportation costs, but also the connectivity reliability of straits and canals when choosing routes for crude oil shipping. Second, while many studies of connectivity reliability have been conducted on road networks (Mine and Kawai 1982; Reed et al. 2019), very few have been produced in the field of maritime research. Even among these numerous studies of road networks, the dependence structure between risk events has gone largely ignored. This paper pioneers a more accurate metric for evaluating the connectivity reliability of straits and canals by addressing precisely this interdependence among risk events. Moreover, based on the analysis of these risk dependences, we can estimate the impact of a change in one risk event's likelihood on the likelihood of other risk events, as well as on overall connectivity reliability. From this, we can propose several measures to improve connectivity reliability. Third, we apply our method to a case study of China's crude oil imports. Navigation through Gwadar Port promises to provide an alternative maritime route for China's crude oil imports and thereby to improve energy import reliability. It remains unknown, however, what effects the opening of this new port will have on route choice for Chinese crude oil shipping, and to what extent it will reduce China's dependence on traditional maritime transportation routes. Our proposed method enables us to model the complex consequences of different scenarios.

The rest of this paper is organized as follows: The relevant literature is reviewed in Section 2. Section 3 describes the problem and presents the mathematical formulation of the model, while Section 4 illustrates the efficiency of our model through a case study. The results are analyzed and discussed, followed by the conclusions and implications laid out in Section 5.

2. Literature review

The first stream of literature relevant to our study concerns the maritime transportation of crude oil. Most of the intercontinental crude oil trade is conveyed by ship, and transportation costs are the major consideration in any proposed adjustments to shipping routes (Yamashita et al. 2019; Wen et al. 2016; Yahyaoui et al. 2021). In addition to the shipping costs, the global trend towards reductions in shipping emissions has led to greater consideration of environmental effects produced by crude oil transportation (Wu et al. 2022; Muhammad and Long 2020; Zavitsas et al. 2018).

In the consideration of transportation costs for crude oil, mixed-integer programming models have long been established as the primary method for route selection and voyage scheduling (Nishi and Izuno 2014; Pinto et al. 2018). These models are used to determine the best transportation route options, usually with the objective of minimizing total transportation costs (Faury et al. 2020; Hennig et al. 2012, 2015). Environmental effects are generally considered along with the costs of selecting different routes, and the carbon emissions of crude oil transportation along various possible routes are estimated (Greene et al. 2020). In order to model these two factors and identify the best possible routes for oil transportation, either the multi-objective approach (Atmayudha et al. 2021) or the multi-criteria decision making technique (Ur Rehman and Ali 2021; Wen et al. 2019) is usually proposed. The results of these studies show that environmental emissions do have an impact on route choice (Atmayudha et al. 2021; Wen et al. 2019). Regardless of the different methodological approaches employed by these studies, transportation reliability yet remains largely neglected. The vulnerability of the straits and canals so vital to maritime transportation to disruption demands appropriate attention to connectivity reliability in order to further ensure the security of crude oil transportation.

The second stream of literature of primary concern to us is the body of work specifically related to the evaluation of connectivity reliability. The first measure of a transportation network's connectivity reliability was proposed by Mine and Kawai (1982), and considers the probability that specific origin-destination (OD) pairs within a network remain connected when links are subject to complete failures. Binary variables are used to describe the two possible operating states of a link, namely, either full-capacity operation or disconnected. Iida and Wakabayashi (1989) extended this measure of terminal connectivity reliability to calculating the connectivity reliability between k nodes and the connectivity reliability of the network as a whole.

Since these initial efforts, the majority of studies related to connectivity reliability have focused on road networks. The methods for calculating network connectivity reliability generally fall into either analytical or approximation methods (Rivera-Royero et al. 2022). Analytical approaches mainly include Boolean algebra (Wakayabashi and Iida 1992), graph theory (Bell and Iida 1997), and minimal path and cut set algorithms (Bai et al. 2015; Reed et al. 2019; Forghani-elahabad et al. 2019). Approximation methods usually rely on Monte Carlo simulations (Zhao et al. 2015). Notably, several new methods have been recently introduced into the analysis of connectivity reliability in transportation networks. Wu et al. (2013) suggested using network connectivity entropy for evaluating connectivity reliability, and conducted a case study of the Nanjing metro network. Liu et al. (2022), meanwhile, considered passengers' travel behaviors and employed their acceptable trip time to estimate the connectivity reliability of a rail transit network.

Although the investigation of connectivity reliability in these studies has proven fruitful, all of these studies pay attention to either a road or rail network. From a methodological perspective, this means that the connectivity reliability of individual links or nodes is already known when they calculate a network's connectivity reliability. Simultaneously, the research into connectivity reliability in shipping is largely absent. Recently, the Russia-Ukraine war had great impact on the transportation reliability of crude oil. The war induced high geopolitical risk, and the transportation node's disruption risk increased significantly. Some reports clearly indicated that the war affected the transportation and supply of crude oil (Global Business Outlook 2022). Because of the lack of data, there are few quantitative studies and discussions on this issue yet. It is crucial to develop methods to understand the impact from these risks on the connectivity reliability of crude oil transportation. Although a few studies of the general vulnerability and resilience of maritime transportation networks have been conducted, measures of connectivity reliability specifically remain undeveloped. In practice, these studies of vulnerability and resilience address the effects of disruptions of arcs or nodes on a transportation network in hindsight. Vulnerability specifically refers to the abnormal sensitivity of a transportation network to internal or external risk scenarios, and it measures the increase in costs caused by disruptions (Pan et al. 2021; Liu et al. 2017; Wen et al. 2022). Resilience, on the other hand, refers to the ability of a transportation network to recover quickly after one or more severe disruptions. This measure emphasizes the overall performance of a transportation network in responding to damage and returning to a normal state over a period of time. In quantifying resilience, the recovery time becomes one of the important indicators (Wang and Yuen 2022; Dui et al. 2021; Poo and Yang 2022; Ahmadian et al. 2020). By contrast, calculating the connectivity reliability (the probability that given transportation arcs (i.e., straits and canals) remain connected when subjected to risk events) provides a powerful potential planning and forecasting mechanism that has as yet received little attention in maritime transportation literature. The foundation of such an analysis, that is, the dependence between various risk events has also not been taken into consideration. Any truly applicable measure of connectivity reliability must take into account the interrelation of risk events and the dependence structure between them.

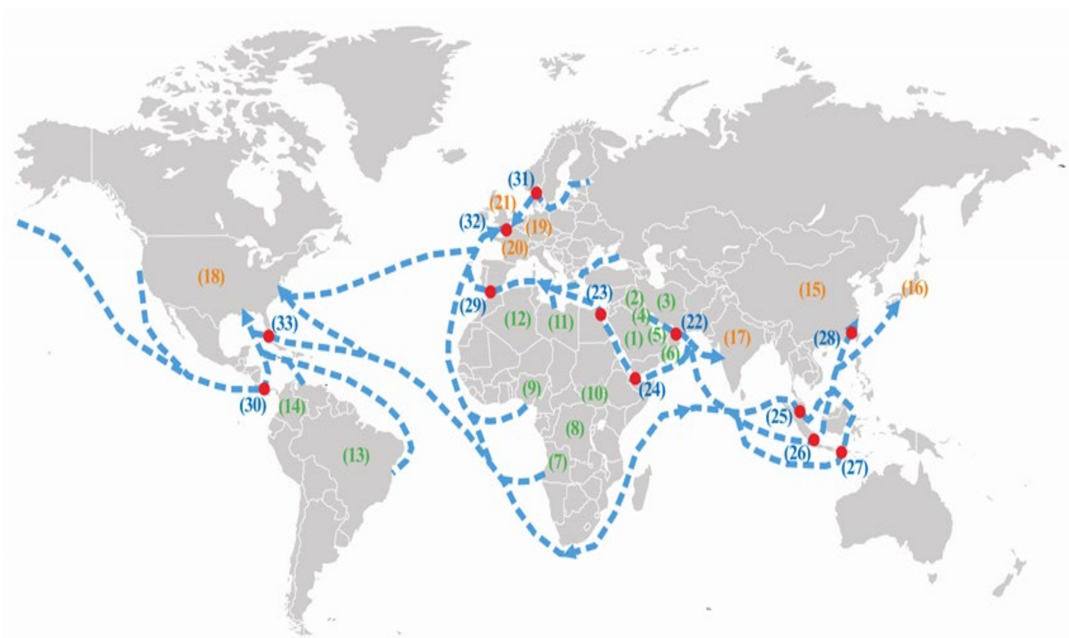
In summary, we propose a multi-objective programming model for shipping route choices. Our work is one of the first studies to consider connectivity reliability as the other significant objective paired with transportation costs. In addition, we develop a vine copula approach, a method that is widely adopted to characterize dependence between variables, in order to quantify the dependence structure between multiple risk events and evaluate the connectivity reliability of straits and canals. In practice, we apply our model to an urgent problem, which allows us to provide practical and meaningful policy implications that can be referred to widely by decision-makers evaluating energy transportation corridors.

3. Methodology

In this section, we present a bi-objective optimization model of shipping route choices for crude oil that simultaneously considers connectivity reliability and transportation costs. In particular, we apply vine copula, a method that is widely used to model the dependence of interrelated variables, to measure the connectivity reliability of straits and canals.

3.1 Problem description

Figure 1 shows the maritime transportation network of the global crude oil trade. The main exporters include countries in the Middle East (such as Saudi Arabia and Iraq), African countries (such as Angola and Congo), and Latin American countries such as Brazil (denoted in green). Major importers include Asian countries (such as China and Japan), European countries (such as the United Kingdom and France), and American countries such as the United States (denoted in yellow). The key straits and canals include the Strait of Hormuz, the Suez Canal, the Bab-el-Mandeb, and the Strait of Malacca, to name only a few (denoted in blue).



(1)	Saudi Arabia	(15)	China	(22)	Strait of Hormuz
(2)	Iraq	(16)	Japan	(23)	Suez Canal
(3)	Iran	(17)	India	(24)	Bab-el-Mandeb
(4)	Kuwait	(18)	United States	(25)	Strait of Malacca
(5)	United Arab Emirates	(19)	Germany	(26)	Sunda Strait
(6)	Oman	(20)	France	(27)	Lombok Strait
(7)	Angola	(21)	United Kingdom	(28)	Taiwan Strait

(8) Congo
(9) Nigeria
(10) South Sudan
(11) Libya
(12) Algeria
(13) Brazil
(14) Colombia

(29) Strait of Gibraltar
(30) Panama Canal
(31) Danish Strait
(32) English Channel
(33) Florida Strait

Figure 1. Maritime transportation network of crude oil

We build a simplified schematic diagram of a maritime transportation network for importing crude oil based on Figure 1 (see Figure 2) and construct our model of the shipping network. Let $G = (N, A)$ denote the maritime transportation network for crude oil imports, as shown in Figure 2. N represents the set of nodes, and A the set of arcs. The set of exporters is denoted by N_1, the importer is denoted by N_2, and the set of other nodes in the network is denoted by N_3, where $N=N_1 \cup N_2 \cup N_3$. The set of straits and canals (denoted by A_1) comprises the arc set, and the set of other transportation arcs are denoted by A_2, where $A=A_1 \cup A_2$. The connectivity reliability of arcs $(i,j) \in A_1$ is affected by various risk events, and is within the range of (0,1), while the connectivity reliability of arcs $(i,j) \in A_2$ is 1.

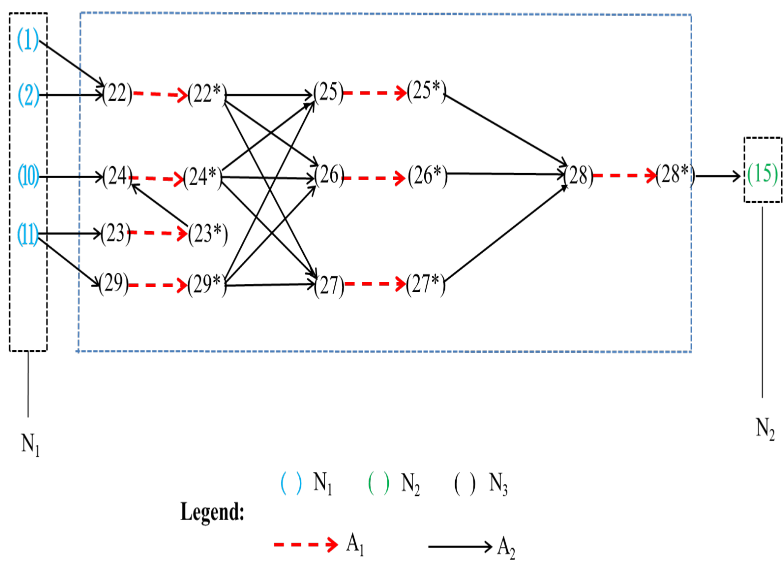


Figure 2. A schematic diagram of global crude oil transportation network

3.2 Mathematical formulation

In this section, we will construct a bi-objective optimization model to solve the maritime transportation route choice problem in a manner that considers both transportation costs and connectivity reliability. We make the following assumptions for model formulation. First, we assume that the transportation cost of an arc is proportional to its length. Second, the shipping company that transports the crude oil imports is regarded as a single entity with a heterogeneous fleet of vessels, including very large crude carriers (VLCCs) and ultra large crude carriers (ULCCs), in addition to Suezmax, Aframax and Panamax vessels. Vessels of each type can only operate along compatible routes. For example, a fully laden VLCC cannot pass through the Suez Canal. Third, the planning horizon is assumed to be one year.

We propose three decision variables in our study. The first is the volume of crude oil transported along each arc. Each arc has its own connectivity reliability and transportation distance (which corresponds to the transportation cost of that arc), and we determine the volume that should be transported via a given arc so as to minimize the total costs and maximize network reliability. This measure is associated with the number of each type of vessel deployed and the volume transported on each route, which are the other two decision variables. The notations used are as follows:

Sets

K Set of OD pairs

N_1 Set of exporters

N_2 The importer

N_3 Set of other nodes

N Set of all nodes in the maritime transportation network for crude oil imports, $N=N_1 \cup N_2 \cup N_3$.

A_1 Set of strait and canal arcs

A_2 Set of other arcs

A Set of all arcs in the maritime transportation network for crude oil imports, $A= A_1 \cup A_2$

L Set of crude oil vessel types

M Set of routes for the OD pairs

Parameters

Q_i Volume of crude oil imported from exporter i

V_l Number of vessels of the lth type

C_l Average carrying capacity of a vessel of the lth type

p_{ij} Transportation cost per ton on arc ij

D Demand for crude oil

H_k^m Maximum carrying capacity of a vessel on route m of OD pair k

z_{ij} Connectivity reliability of arc ij

q_{lm}^k Cargo-carrying capacity of a vessel of the lth type on route m of OD pair k

c_{lm}^k Number of round-trip voyages of the lth type vessel on route m of OD pair k

$\delta_{ij}^{m,k}$ $\in \{0,1\}$, 1 if route m of OD pair k uses arc ij, and 0 otherwise

Decision variables

x_{ij} Volume of crude oil transported on arc ij

f_m^k Volume of crude oil transported on route m of OD pair k

V_{lm}^k Number of lth type vessels deployed on route m of OD pair k for transporting imported crude oil

Based on the previous analysis, the model is established as follows.

$$Min \quad \sum_{i\in N}\sum_{j\in N} x_{ij}\, p_{ij} \tag{1}$$

$$Max \quad \sum_{i\in N}\sum_{j\in N} x_{ij}\, z_{ij} \tag{2}$$

Subject to

$$\sum_{\substack{j\in N\\ (i,j)\in A}} x_{ij} = Q_i\,, \quad i\in N_1 \tag{3}$$

$$\sum_{\substack{j\in N\\ (j,N_2\in A)}} x_{jN_2} = \sum_{i\in N_1} Q_i \tag{4}$$

$$\sum_{\substack{j\in N\\ (j,i)\in A}} x_{ji} = \sum_{\substack{j\in N\\ (i,j)\in A}} x_{ij}\,, \quad i\in N_3 \tag{5}$$

$$\sum_{\substack{j\in N\\ (j,N_2)\in A}} x_{jN_2} \ge D \tag{6}$$

$$x_{ij} = \sum_k\sum_m \delta_{ij}^{m,k} f_m^k\,, \quad i\in N, j\in N, k\in K, m\in M \tag{7}$$

$$f_m^k = \sum_l q_{lm}^k c_{lm}^k V_{lm}^k\,, \quad m\in M, k\in K \tag{8}$$

$$q_{lm}^k = \min\left\{C_l, H_k^m\right\} \quad l\in L, m\in M, k\in K \tag{9}$$

$$\sum_m\sum_k V_{lm}^k \le V_l\,, \quad l\in L \tag{10}$$

$$x_{ij}\ge 0\,, \quad i\in N, j\in N \tag{11}$$

$$f_m^k \ge 0, V_{lm}^k \ge 0\,, \text{ and } V_{lm}^k\in Z\,, \quad l\in L, m\in M, k\in K \tag{12}$$

Objective function (1) minimizes the total transportation costs of crude oil en route from exporters to the importer. Objective function (2) maximizes total connectivity reliability. Constraints (3)-(5) are the flow conservation constraints for x_{ij}. Constraint (3) indicates that, for exporters, the total volume transported from each exporter is equal to its export volume to the importer. Constraint (4) stipulates that the volume transported to the importer is equal to the total import volume from all exporters. Constraint (5) specifies that, for other nodes, the volumes transported to them are equal to the volumes transported out of them. Constraint (6) ensures that the total volume transported to the importer can meet demand. Constraint (7) represents the relationship between the flow of arcs and routes. Constraint (8) indicates that the volume of crude oil transported on route *m* of OD pair *k* is related to the number of vessels deployed on that route. In Constraint (9), q_{lm}^k concerns the average carrying capacity of a vessel of the *l*th type, and it depends on the route along which the vessel is deployed. For example, a fully laden VLCC cannot pass through the Suez Canal; therefore, q_{lm}^k is equal to the smaller value between C_l and H_k^m. Constraint (10) is the vessel fleet constraint and denotes that, for each vessel type, the sum of vessels deployed on all routes should not exceed the total number of that vessel type. Constraints (11) and (12) define the domains of the decision variables.

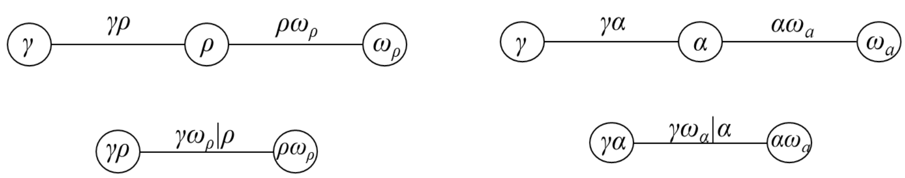
We introduce *w* as the carrier's preference toward connectivity reliability, which determines the route choices of a shipping company, and assume $0 \le w \le 1$. If the shipping company places more weight on minimizing transportation costs rather than on maximizing reliability, then the value of *w* will be small. On the other hand, if more emphasis is placed on connectivity reliability at the expense of transportation costs (as can occur in the importation of a strategic resource like crude oil), then the value of *w* will be large. With the *w*, the bi-objective model can be transformed into a single-objective programming model, and the trade-off between the two conflicting objectives can be resolved. That is:

$$Min \ (1-w)\cdot\sum_{i\in N}\sum_{j\in N} p_{ij}^{\wedge}\cdot x_{ij} + w\cdot\sum_{i\in N}\sum_{j\in N}(1/z_{ij})^{\wedge}\cdot x_{ij} \qquad (13)$$

subject to constraints (3)-(12). Here, $1/z_{ij}$ is the inverse of connectivity reliability, which can be seen as the transportation risk for arc *ij*, and the problem of maximizing connectivity reliability is solved by minimizing transportation risk. In addition, $p_{ij}^{\wedge}$ and $(1/z_{ij})^{\wedge}$ are the values of min-max normalization processing, which are within the range [0, 1], and the dimensional effects do not exist (Jain and Bhandare 2011). We thus have a mixed-integer programming model, which we can solve with Cplex.

3.3 Evaluation of connectivity reliability

From the Global Integrated Shipping Information System (GISIS) and related research reports (Bailey and Wellesley 2017; EIA 2017), four risk events are commonly identified as significantly affecting the connectivity reliability of straits and canals in the crude oil seaborne trade network. These events are heavy weather, vessel incidents, piracy and maritime terrorism, and political instability and military conflict. Piracy and maritime terrorism, as well as vessel incidents, are the risk events that most directly affect connectivity reliability, although in most cases they do not occur simultaneously. Heavy weather and political instability and military conflict will affect both the occurrence of piracy and maritime terrorism and vessel incidents. Risk events, therefore, are divided into two scenarios. Scenario 1 includes three risk events: piracy and maritime terrorism (ρ), heavy weather during the commission of piracy or maritime terrorism (ω_ρ), and political instability and military conflict (γ). Scenario 2 encompasses the following events: vessel incidents (α), heavy weather at the time of a vessel incident (ω_a), and political instability and military conflict (γ), as shown in Figure 3.



Scenario 1 Scenario 2

Figure 3. Risk events in Scenarios 1 and 2

In addition to establishing the interrelated nature of the various risk events, we further refine the model by referencing the product reliability evaluation method found in Yin et al. (2018). We assume that, given the values of heavy weather and political instability and military conflict, if the number of piracy or vessel incidents is not greater than the critical value, then the straits or canals can be considered connected. Thus, connectivity reliability is a conditional probability that can be obtained by constructing the conditional distribution of various risk events.

Vine copula has been widely used in financial, hydrologic, and engineering fields to model the dependence of interrelated variables. Its advantage over the correlation approach is that it can deal with any non-linearity, asymmetry, and tail dependence of the variables (Aas 2016; Farrokhi et al. 2021). In this paper, we apply vine copula to describe the dependence structure between multiple risk events, and to construct the conditional distribution. Consider a vector $Y_1=(\gamma, \rho, \omega_\rho)$ of the risk events enumerated in Scenario 1, with the joint distribution function $F=F(\gamma, \rho, \omega_\rho)$, and the marginal distributions of risk events $F_1=F(\gamma)$, $F_2=F(\rho)$, $F_3=F(\omega_\rho)$. According to Sklar's theorem (Sklar 1959), the joint probability distribution of the risk events established in Scenario

1 can be expressed as follows:

$$F(\gamma,\rho,\omega_\rho)=C(F(\gamma),F(\rho),F(\omega_\rho)) \tag{14}$$

The copula function can thus be regarded as the joint distribution function of risk events (γ, ρ, ω_ρ). The copula function reflects information regarding the dependence structure between risk events, and this structure has nothing to do with the marginal distribution of risk events. The copula is a function determined solely by the dependence structure between risk events.

The joint probability density function of the risk events in Scenario 1 can then be expressed as:

$$f(\gamma,\rho,\omega_\rho)=c(F(\gamma),F(\rho),F(\omega_\rho))\cdot(f(\gamma)\cdot f(\rho)\cdot f(\omega_\rho)) \tag{15}$$

where c indicates copula density. The joint probability density function of the risk events includes two parts: one is the density function of the copula (which contains all of the information about the dependence structure of the risk events) and the other is the product of the marginal density function of each risk event.

Most studies focus on the establishment of bivariate copulae and parameter estimations (Marri and Moutanabbir 2022). It becomes difficult to solve Equation (15) when the dimension of risk events increases (Aas et al. 2009). Vine copulas are graphical models that allow us to decompose Equation (15) in a hierarchical manner via a series of bivariate copula densities (pair copulas) of risk events, as shown in Figure 3. Mathematically, we can describe the decomposition of Equation (15) as follows:

$$\begin{aligned} f(\gamma,\rho,\omega_\rho;\theta)=f(\gamma)\cdot f(\rho)\cdot f(\omega_\rho)\cdot c_{\gamma\rho}\left\{F(\gamma),F(\rho)\right\}\cdot c_{\rho\omega_\rho}\left\{F(\rho),F(\omega_\rho)\right\} \\ \cdot c_{\gamma\omega_\rho|\rho}\left\{F(\gamma\mid\rho),F(\omega_\rho\mid\rho)\right\} \end{aligned} \tag{16}$$

where $c_{\gamma\rho}$, $c_{\rho\omega\rho}$, and $c_{\gamma\omega\rho|\rho}$ are the bivariate copula densities of risk events, and θ is the set of all parameters in the vine copula.

The above vine copula construction of risk events involves marginal conditional distributions of the form $F(u|\boldsymbol{v})$. Furthermore, Joe (1996) showed that:

$$F(u\mid\boldsymbol{v})=\frac{\partial C_{u,v_j|\boldsymbol{v}_{-j}}\left\{F(u\mid\boldsymbol{v}_{-j}),F(v_j\mid\boldsymbol{v}_{-j})\right\}}{\partial F(v_j\mid\boldsymbol{v}_{-j})} \tag{17}$$

where v_j is an arbitrarily chosen risk event from events vector $\boldsymbol{v}$, $\boldsymbol{v}_{-j}$ is $\boldsymbol{v}$ excluding this risk event, and $C_{u,vj|v\text{-}j}$ is a conditional bivariate copula between pairwise risk events.

More specifically, in the case when $\boldsymbol{v}$ includes only one risk event:

$$F(u \mid v) = \frac{\partial C_{uv}\left\{F(u), F(v)\right\}}{\partial F(v)} \tag{18}$$

In addition, the function $h\left(u, v, \Theta\right)$ is used to represent this conditional distribution function of risk events when *u* and *v* are uniform (Aas et al. 2009):

$$h(u, v, \Theta) = F(u \mid v) = \frac{\partial C_{uv}\left\{F(u), F(v)\right\}}{\partial F(v)} \tag{19}$$

where the second variable of $h\left(u, v, \Theta\right)$ is always the conditional risk event and the set of parameters of the copula of risk events *u* and *v* is denoted by Θ.

Therefore, the conditional probability distribution for the risk events outlined in Scenario 1 $F(\rho|\gamma, \omega_\rho)$ can be expressed as:

$$\begin{aligned} F(\rho \mid \gamma, \omega_\rho) &= \frac{\partial C_{\rho,\gamma|\omega_\rho}\left\{F(\rho \mid \omega_\rho), F(\gamma \mid \omega_\rho)\right\}}{\partial F(\gamma \mid \omega_\rho)} \\ &= \frac{\partial C_{\rho,\gamma|\omega_\rho}\left[h(F(\rho), F(\omega_\rho), \Theta_{\rho\omega_\rho}), h(F(\gamma), F(\omega_\rho), \Theta_{\gamma\omega_\rho})\right]}{\partial\left[h(F(\gamma), F(\omega_\rho), \Theta_{\gamma\omega_\rho})\right]} \end{aligned} \tag{20}$$

It can also be expressed in the following manner:

$$\begin{aligned} &F\left(\rho \mid \gamma, \omega_\rho\right) = h[h\left(F(\rho), F(\omega_\rho), \Theta_{\rho\omega_\rho}\right), \\ &h\left(F(\gamma), F(\omega_\rho), \Theta_{\gamma\omega_\rho}\right), \Theta_{\rho\gamma|\omega_\rho}] \end{aligned} \tag{21}$$

Similarly, the conditional probability distribution for the risk events described in Scenario 2 $F(\alpha|\gamma, \omega_a)$ can be expressed as:

$$\begin{aligned} &F\left(\alpha \mid \gamma,\ \omega_a\right) = h[h\left(F(\alpha), F(\omega_a), \Theta_{\alpha\omega_\alpha}\right), \\ &h\left(F(\gamma), F(\omega_a), \Theta_{\gamma\omega_\alpha}\right), \Theta_{\alpha\gamma|\omega_\alpha}] \end{aligned} \tag{22}$$

As for the choice of bivariate copula types for pair risk events, we consider five commonly used bivariate copulas that can describe different tail dependences of the risk events, namely Gaussian, Student, Frank, Clayton and Gumbel copulas. The Frank copula and Gaussian copula can describe either strong negative or positive dependence between the risk events, and are symmetric in both their upper and lower tails. The Clayton copula and the Gumbel copula can describe only positive dependence, and the Clayton copula exhibits strong lower tail dependence, while the Gumbel copula exhibits strong upper tail dependence of risk events. The Student copula, meanwhile, is both lower and upper tail dependent (Joe 1997; Aas et al. 2009). The Akaike information criterion (AIC) can calculate which copula best fits the bivariate pair of risk events, so we employ the AIC to select the appropriate type of pair-copula (Aas et al. 2009).

With regard to the estimation of the parameters of the vine copula, this paper employs stepwise semi-parametric estimators (SSP). The parameters are estimated level by level, plugging in parameters from previous levels at each step (Aas et al. 2009; Hobæk Haff 2012, 2013). Based on the estimated parameters of the bivariate copulas, $F(\rho|\gamma, \omega_\rho)$ and $F(\alpha|\gamma, \omega_a)$ can be calculated. We then combine the conditional probabilities of the two scenarios to calculate connectivity reliability. Since piracy and maritime terrorism and vessel incidents are equally important risk events, we assign the same weights to these two conditional probabilities, and derive the connectivity reliability from the sum of these probabilities.

4. Case study

China, as one of the largest importers of crude oil, relies on supplies from multiple countries. Recently, the construction of Gwadar Port in Pakistan has provided China with a new route option. In this section, we will use our model to testify whether the optimal maritime transportation routes include Gwadar Port as an option when the transportation reliability of different channels are considered.

4.1 Problem setting

The China Overseas Port Holding Company took over the operation of Gwadar Port in 2013, and on November 13, 2016, Gwadar Port was officially opened to navigation. Gwadar Port is located at the mouth of the Persian Gulf (about 400 km from the Strait of Hormuz), and is a deep-water port with the capacity to accommodate 80-100,000 DWT oil tankers. China and Pakistan are both interested in the construction of a new crude oil pipeline, such that crude oil from the Middle East, Africa, and Latin America can be transported by sea to Gwadar Port, and then via pipeline to China. Navigation through Gwadar Port is expected to circumvent traditional maritime routes, such as those through the Straits of Malacca.

When determining the major exporters of crude oil to China, we select Saudi Arabia, Iraq, Iran, Kuwait, United Arab Emirates (UAE), and Oman in the Middle East; Angola, Congo, South Sudan, and Libya in Africa; and, Brazil, and Colombia in Latin America (Wang et al. 2020). The volumes imported from these countries equate to 67% of China's total imports of crude oil in

2021. The import volumes from these exporters are shown in Table 1. Referring to Figure 1, the straits, canals, and ports involved in China's crude oil maritime transportation are the Strait of Hormuz, the Strait of Malacca, the Sunda Strait, the Lombok Strait, the Strait of Gibraltar, the Taiwan Strait, the Bab-el-Mandeb, the Suez Canal, the Panama Canal, Kyaukpyu Port, and Gwadar Port, as shown in Figure 4. The annual transportation capacities of the China-Pakistan and China-Myanmar crude oil pipelines are 20 and 22 million tons, respectively (Wang et al. 2018).

(34) Gwadar Port (35) Kashgar (36) Kyaukpyu Port (37) Kunming

Figure 4. Maritime transportation network of China's oil imports

Table 1. Import volumes from exporters

Region	Crude oil exporter	Import volume (tons)
Middle East	Saudi Arabia	87,567,606
	Iraq	54,079,431
	Iran	260,312
	Kuwait	30,163,415
	United Arab Emirates	31,937,527
	Oman	44,815,401
West Africa	Angola	39,154,905
	Congo	8,928,017
North Africa	South Sudan	571,894
	Libya	6,137,688
Latin America	Brazil	30,301,484
	Colombia	9,461,824

Data source: International Trade Center

We choose four measurements as proxies for the four risk events, as shown in Table 2. Piracy and armed robbery data is collected from the Global Integrated Shipping Information System (GISIS) of the International Maritime Organization (IMO, http://gisis.imo.org/Public/PAR/Default.aspx). According to the coordinate and location information for the piracy, the number of piracy for each strait or canal can be collected. The vessel incidents data is also collected from GISIS. The daily wind speed grid data is collected and the data is produced by the Remote Sensing Systems (http://www.remss.com). It is a spatially complete dataset available every six hours and closely collocated in time and space. Based on the longitude, latitude and time of the piracy or vessel incidents, the wind speed when piracy and armed robbery happened or vessel incidents happened can be obtained. As for the political risk, we refer to the index released by the PRS Group (https://www.prsgroup.com), which can reflect the geopolitical risk of the region where the nodes belong to. For example, with the breakout of the war between Russia and Ukraine, the risk index for the two countries decreased from 59.5 to 52.5, and from 64.5 to 58.5, respectively. Concretely, in our study, the value of the political risk for a strait is represented by the annual average risk value of countries it affiliates to. For example, as for the Malacca Strait, the political risk is expressed as the average of the political risk index of Singapore, Malaysia and Indonesia.

Based on the GISIS, daily wind speed and political risk index database mentioned above, we collect data on each of the four risk events for the 11 straits, canals and ports, and it costs us almost one year for data collection over the course of the period from 1999 to 2021. We take the median number of piracy and vessel incidents in 2021 in the designated straits, canals, and ports as the critical value. We then calculate the conditional probability and the connectivity reliability values using the model proposed in Section 3.3. All calculations are done with *R* software, and the results are listed in Table 3. As shown in Table 3, the connectivity reliability of the Strait of Malacca, the Bab-el-Mandeb and Gwadar Port is relatively low; while the connectivity reliability of the Strait of Gibraltar and the Lombok Strait is high.

Table 2. Proxies and data sources for risk events

Risk events	Proxies	Data sources
Piracy and maritime terrorism	Number of piracy and armed robbery	GISIS
Vessel incidents	Number of vessel incidents	GISIS
Heavy weather	Sea surface wind speed	Remote Sensing System

Political instability and military conflict	Political risk index	PRS Group

Note: A higher score in the political risk index indicates lower risk

Table 3. The connectivity reliability of straits, canals, and ports

Straits, canals, and ports	Conditional probability in Scenario 1	Conditional probability in Scenario 2	Connectivity reliability
Strait of Malacca	0.2763	0.5212	0.3988
Sunda Strait	0.4279	0.9334	0.6807
Lombok Strait	0.7717	0.8869	0.8293
Taiwan Strait	0.8830	0.6688	0.7759
Strait of Hormuz	0.4538	0.5859	0.5199
Bab-el-Mandeb	0.1599	0.8189	0.4894
Strait of Gibraltar	0.9656	0.6722	0.8189
Suez Canal	0.7076	0.6219	0.6648
Panama Canal	0.7735	0.7525	0.7630
Gwadar Port	0.5074	0.5563	0.5319
Kyaukpyu Port	0.6061	0.7351	0.6706

Chinese seaborne crude oil imports account for 17.8% of the World's total seaborne oil trade, according to the Clarksons database. We thus multiply the number of vessels of each type in the global fleet by 17.8% in order to estimate the number of each vessel type used to transport Chinese crude oil imports (Wang et al. 2018). According to Cheng and Duran (2004), a typical, unitary measure of the total transportation cost of oil is within the range of US $1.50-3.00 per barrel of crude oil. We assume that the transportation cost from Iran to China is US $1.50 per barrel of crude oil. Given the transportation distance of each arc within the transportation network and the conversion relationship between tons and barrels of crude oil, we can calculate the transportation cost per ton along each arc of the major routes of Chinese oil imports (Wang et al. 2020). Most researchers believe that routing through Gwadar Port provides a cheaper alternative to the traditional maritime transportation routes, such as those through the Strait of Malacca, because the port significantly reduces the transportation distance (Wang and Yau 2018; Khan 2013; Malik 2012; Guo et al. 2019). Therefore, we set the transportation cost of the China-Pakistan and China-Myanmar pipelines according to the transportation distance ratio of pipelines to shipping routes. We assume that the pipelines are constructed by the government (Ur Rehman and Ali 2021), and that vessels have already been bought by the shipping company. Thus, for the purposes of our model, we do not consider the fixed investment in pipelines and vessels. The information of each vessel type is shown in Table 4. The number of available operating days per year for each vessel type is assumed to be 345 days (Wang et al. 2018).

Table 4. Information for each vessel type

Vessel type	Average carrying capacity (DWT)	Speed (knots)	Number
VL/ULCC	307,539	15.7	151
Suezmax	155,196	15.1	111
Aframax	107,934	14.9	131
Panamax	72,648	14.9	17

Data source: Clarksons Research Services

4.2 Results

In this section, we will first analyze the impact of the dependence structure of risk events on connectivity reliability, and then discuss the route choice results.

4.2.1 Impact of dependence structure on connectivity reliability

Based on the model proposed in Section 3.3, the dependence structure of risk events can be calculated as shown in Figure 5. We use the Malacca and Sunda Straits, along with Gwadar Port, to illustrate the impact of the dependence structure on connectivity reliability.

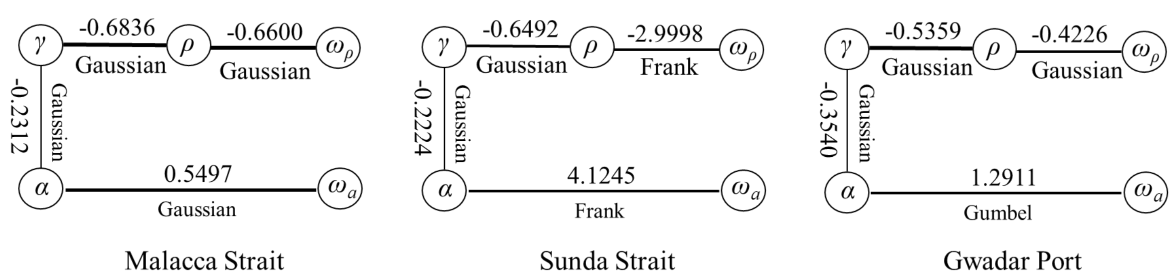


Figure 5. Dependence structure of risk events

Note: The parameter value of the Gaussian copula is within the range (-1,1); the parameter value of the Gumbel copula is within the range [1, +∞); the parameter value of the Frank copula is within the range (-∞,0) ∪ (0, +∞)

It can be observed that there are various dependence structures of risk events. Concretely, there is a strong negative dependence between the value of the political risk factor and the number of piracy (e.g., -0.5359 for Gwadar Port). This is expected because, as stated previously, a high score in the political risk index released by the PRS Group represents lower potential political instability, and thus the number of pirate attacks will be smaller. The strong negative dependence between the sea surface wind speed and the number of piracy (-0.6600 for the Malacca Strait, for example) suggests that heavy weather also plays a deterring role in piracy. On the other hand, heavy weather demonstrates a strong positive influence on the number of vessel incidents, as evidenced by the strong positive dependence between them (0.5497 for the Malacca Strait). In terms of political risk and the number of vessel incidents, a relatively weak negative dependence exists between these two risk factors (-0.2312 for the Malacca Strait).

Moreover, the tail dependences between risk events demonstrate variance between the two straits and Gwadar Port. For Gwadar Port, an upper tail dependence exists between sea surface wind speed and vessel incidents (according to the Gumbel copula), which indicates a stronger dependence when two risk events are both more likely to occur. In our case, when sea surface wind speed increases greatly, the probability of vessel incidents also increases significantly also. For the Malacca and Sunda Straits, symmetric tail dependence exists between these two risk events (according to both Gaussian and Frank copulas). This outcome indicates that, regardless of whether these two events are more or less likely to occur, the dependence is the same. Therefore, when in heavy weather near Gwadar Port, relevant precautions should be taken to avoid primarily vessel incidents, which would effectively improve the connectivity reliability of the port. As for political risk and the number of piracy, symmetric tail dependences exist between these two events for both the straits and for Gwadar Port. This suggest that reducing political risk should also produce a decreasing rate of pirate attacks and maritime terrorism. From this we can conclude that improvements in local political conditions near one of these nodes will likely improve connectivity reliability.

These results imply that relatively strong dependences do exist between various risk events and that these relationships affect connectivity reliability. Thus, these dependent relationships cannot be ignored when evaluating connectivity reliability; otherwise, it will lead to faulty estimations. In addition, based on the dependence structures identified in this section for Gwadar Port and the two straits, by mitigating the likelihood of certain risk events, we can effectively improve the connectivity reliability of these transportation arcs.

4.2.2 Route choice discussion

In this subsection, we first analyze a carrier's choice of Gwadar Port given different levels of preference for connectivity reliability. Then, we discuss the potential of Gwadar Port as an alternative route for Chinese oil imports through improving its connectivity reliability.

(1) Carrier's preferences toward Gwadar port

The findings shown in Table 5 suggest that the connectivity reliability of Gwadar Port has a crucial influence on its role in the transportation of crude oil to China. Specially, when the carrier has a higher preference toward transportation cost reduction (w=0.1), we observe that 20 million tons of crude oil are transported via routes through Gwadar Port, which is the upper capacity limit of the China-Pakistan pipeline. This is the maximum volume that Gwadar Port can transport, and accounts for 3.9% of China's total crude oil imports. When the carrier's preference toward connectivity reliability and transportation cost is the same (w=0.5), there are also 20 million tons of crude oil transported via routes through Gwadar Port. When the carrier's preference toward connectivity reliability reaches 0.7 (indicating that the carrier has a relatively high preference toward connectivity reliability), routes through Gwadar Port will not be selected. Alternatively, most of the oil will be transported through the Lombok Strait, as routes through the Lombok Strait are more reliable.

Table 5. Volume of crude oil transported through Gwadar Port and the Malacca, Sunda, and Lombok Straits (million tons)

	w=0.1	w=0.5	w=0.7
whether Gwadar Port is selected	Yes	Yes	No
Gwadar Port	20	20	0
Malacca Strait	0	0	0
Sunda Strait	261.6	188	0
Lombok Strait	0	73.6	281.6

(2) The potential of Gwadar Port as an alternative route for oil transportation

As illustrated in Table 5, when w<0.7, Gwadar Port is fully utilized; when, however, the carrier demonstrates a higher preference for connectivity reliability ($w \geq 0.7$), Gwadar Port's role as a substitute for traditional transportation routes of crude oil is limited. We must further scrutinize the role of Gwadar Port when w is 0.7, and discuss the necessity of connectivity reliability improvement.

Under this circumstance, according to our model, we calculated that when Gwadar Port's connectivity reliability increases by 2.4%, it provides a viable substitute route and its maximum volume for oil transportation will be utilized if the Lombok strait is disrupted. There are two reasons that help to understand this outcome. First, the connectivity reliability of the Malacca Strait from our data analysis is lower than that of Gwadar Port, and the transportation cost of routes through the Malacca Strait is higher than those through Gwadar Port; thus, when the Lombok Strait is disrupted, routes through Gwadar port will be used rather than those through the Malacca Strait. Second, the cost of routes through Gwadar Port is lower than those through the Sunda Strait, and the difference in reliability between Gwadar Port and the Sunda Strait decreases after improvement of Gwadar Port's connectivity reliability. So, when the Lombok Strait is disrupted, part of the volume originally transported through it will be transferred to Gwadar Port, and the other will be rerouted to the Sunda Strait, as shown in Figure 6.

When either the Malacca Strait or the Sunda Strait is disrupted, all crude oil will be transported via routes through the Lombok Strait rather than through Gwadar Port, as exhibited in Figure 6. This is because, although the cost of routes through Gwadar Port is lower than those through the Lombok Strait, the difference in reliability between Gwadar Port and the Lombok Strait remains large after Gwadar Port's connectivity reliability increases by 2.4%. Gwadar Port will thus not be selected by the carrier.

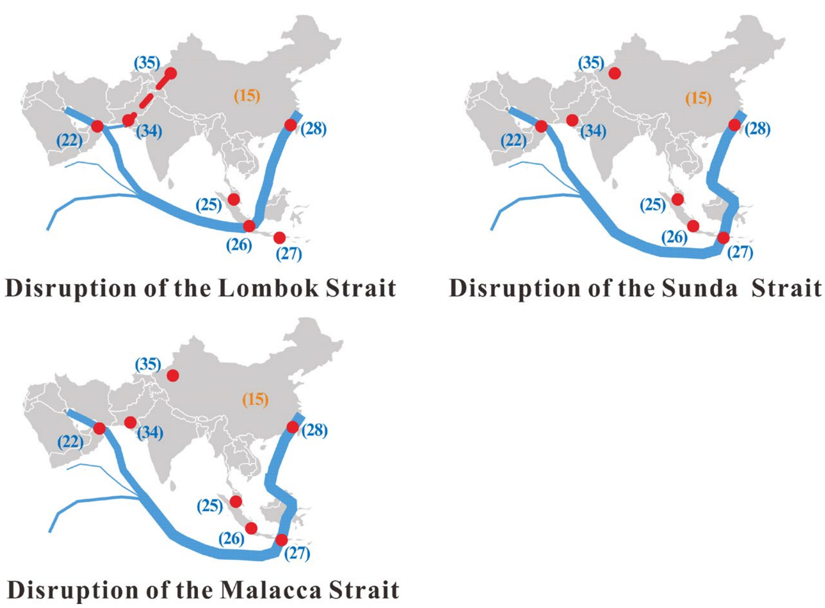


Figure 6. Route choices after Gwadar Port's connectivity reliability increases by 2.4%

When its connectivity reliability increases by 12.2%, about 3.9% of China's total oil imports are transported via routes through Gwadar Port (i.e., its maximum transportation volume) when the Malacca, Sunda, or Lombok Straits are disrupted, as shown in Figure 7. As discussed previously, the connectivity reliability of the Lombok Strait is high, and only when Gwadar Port's connectivity reliability is improved by a larger margin can it serve as a route supplement for the Lombok Strait when either the Malacca or Sunda Straits are disrupted. After the improvements, we expect that the substitution effect of Gwadar Port on traditional maritime transportation routes will likewise increase, and that its strategic role will be fully actualized.

Moreover, when the carrier's preference toward connectivity reliability is high (w=0.9), in order to realize Gwadar Port's full potential as a route alternative, its connectivity reliability must be improved by an even larger margin. That is, only when Gwadar Port's connectivity reliability is improved by at least 16.1% can it provide an alternative in the event that the Lombok Strait is disrupted. If either the Malacca or the Sunda Strait is disrupted, Gwadar Port's connectivity reliability must increase by at least 33.6%. The successful development of Gwadar Port would thus increase its overall utility in reducing reliance on key straits, and significantly improve the reliability of crucial oil imports.

Gwadar Port is geographically important to the Middle East and China, and it has a high political risk. The complex ethnic conflicts and religious antagonism within Pakistan precipitate constant political crises and frequent changes in government. Besides, the prevalence of terrorism, and geopolitical maneuvering between international players such as America, India, Iran, and their policy interests in Gwadar Port also pose challenges to Gwadar Port's operations. These lead to a very high level of political risk in Pakistan, and its political risk index is only 47.3 in 2021, which is much smaller than Singapore's 81.7. The high political risk can induce an increase in piracy and vessel incidents, which reduces the transportation reliability of crude oil through Gwadar Port. Given the dependent relationship between piracy and political risk demonstrated earlier, a reduction of political risk holds substantial promise for improving Gwadar Port's connectivity reliability. In addition, since there is an upper tail dependence between sea surface wind speed and the number of vessel incidents for Gwadar Port, taking better precautionary measures to avoid vessel incidents in heavy weather would also improve Gwadar Port's connectivity reliability.

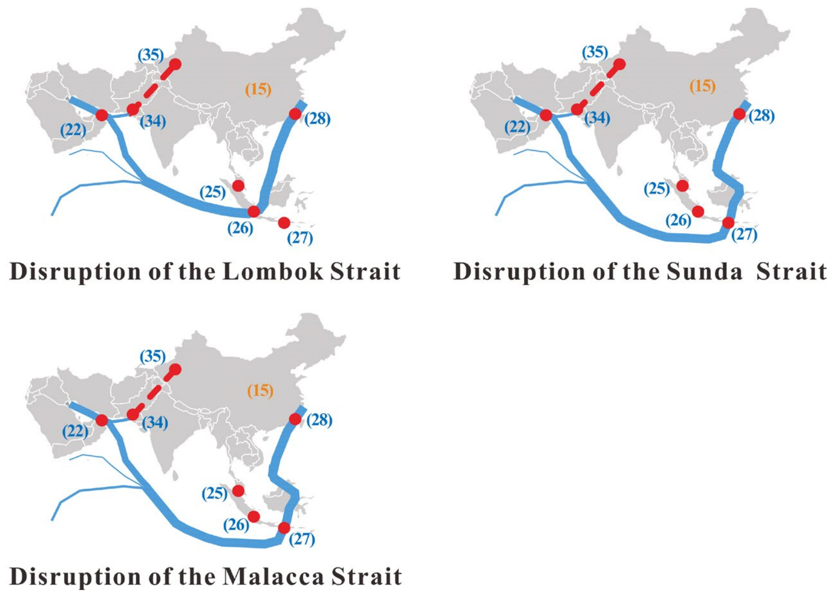


Figure 7. Route choices after Gwadar Port's connectivity reliability increases by 12.2%

5. Conclusions and implications

In this study, we develop a maritime transportation route choice model of crude oil that considers both transportation costs and connectivity reliability. In particular, we propose a connectivity reliability evaluation method that establishes the interdependence between risk events. This method both improves the accuracy of connectivity reliability estimation and provides a reference for development decisions made with the improvement of connectivity reliability in mind. We then apply the model to evaluate the effects of Gwadar Port on maritime route choices for imports of crude oil to China. The results show that the dependence relationship varies between different risk events, and the tail dependences between risk events demonstrate variance across straits and canals. As for Gwadar Port, our results demonstrate that its strategic role has not yet been fully realized. When the carrier's preference for connectivity reliability is less than 0.7, Gwadar Port's potential as a substitute route is fully exploited, and the volume of crude oil it handles is equal to the upper capacity limit of the China-Pakistan pipeline. When the carrier's preference for connectivity reliability is higher ($w \geq 0.7$), however, it cannot serve as an alternate route for crude oil transportation due to its low connectivity reliability.

Several managerial insights emerge from this analysis. First, the dependences between risk events are strong, especially for the relationship between political risk and the number of piracy and armed robbery, and the relationship between sea surface wind speed and the number of vessel incidents. Based on these dependences, an amelioration of political instability will likely reduce the number of piracy and maritime terrorism significantly, thus improving connectivity reliability. Likewise, heavy weather is an important determinant of lower connectivity reliability, and carriers and local authorities alike should seek to implement robust precautions. Second, when $w \geq 0.7$, Gwadar Port's existing connectivity reliability constrains its potential to reduce reliance on traditional maritime transportation routes. If Gwadar Port's substitution role for key straits is to be fully realized, its connectivity reliability needs improvement. When the value of w is 0.7-0.9, if Gwadar Port's connectivity reliability is improved by 2.4%-16.1%, it can provide an alternative route when the Lombok Strait is disrupted. If Gwadar Port's connectivity reliability is improved by 12.2%-33.6%, then its role as a reliable alternative to traditional maritime routes through the Malacca, Sunda, and Lombok Straits will be fully realized. In the short and medium term, taking relevant precautions to avoid more vessel incidents in heavy weather, while also promoting a long-term uplift of Pakistan's political condition are likely two effective ways to improve Gwadar Port's connectivity reliability. Additionally, since the volume of crude oil that Gwadar Port can transport is also dependent on the annual capacity of the China-Pakistan pipeline, a larger pipeline capacity would have beneficial ramifications and should be explored by policymakers and investors looking for opportunities to further develop Gwadar Port.

The war between Russia and Ukraine nowadays has great impact on the global crude oil transportation. For example, as for the Strait of Bosporus, the war will raise its geopolitical risks and increase its disruption probability; the likelihood of vessel incidents caused by the abuse of older tankers due to the sanctions against Russia will also increase. These risk events are interrelated and together affect the strait's connectivity reliability. In the future, with more data becomes available, it will be interesting to apply our model to characterize the dependence of these risk events and evaluate the strait's connectivity reliability, then the crude oil transportation flows change can be estimated considering these risks.

Finally, we note the limitations of the present paper, and the opportunities that they provide for future research directions. We did not evaluate the connectivity reliability of pipelines in our study due to the paucity of data related to pipeline security risks. From a methodological perspective, other approaches to the estimation of connectivity reliability for pipelines would be a worthwhile subject of future study. Besides, for a specific strait or canal, the piracy risk may be higher than vessel incidents, or vice versa. Determining appropriate adjustment parameters to the weights of the two conditional probabilities for specific nodes would also be a possible future extension. Last but not the least, there are multiple ways in defining a risk, the severity of consequence would be considered to define risks in the future study.

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