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Charting sustainable logistics on the 21st-Century Maritime Silk Road: a DEA-based approach enhanced by risk considerations through prospect theory

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This study investigates the sustainable logistics potential of countries along the Maritime Silk Road (MSR), an essential element of the Belt and Road Initiative (BRI), against a backdrop of increasing global emphasis on sustainability and efficient trade practices. Addressing the gap in existing literature, it explores how strategic positioning influences countries' logistics capabilities, integrating risk considerations and behavioral decision-making aspects into the assessment. Through a specialized Data Envelopment Analysis (DEA) model that incorporates Prospect Theory, this research provides a nuanced evaluation of economic performance, energy efficiency, infrastructure robustness, governance quality, and innovation capabilities. The analysis reveals significant findings, such as Vietnam's outstanding economic efficiency, Indonesia's notable achievements in sustainability and governance, and Malaysia's balanced efficiency, which collectively enhance the MSR's logistics framework. Additionally, India, Greece, Djibouti, and Kenya emerge as vital partners due to their diverse strengths. The introduction of a risk-aware DEA model, enriched with behavioral factors, marks a significant advancement in logistics assessment methodologies, offering a more comprehensive understanding of sustainable logistics practices along the MSR. The implications of this study are profound, providing valuable insights for policymakers, investors, and business leaders. It guides strategic decision-making, promoting sustainability in MSR trade activities while aligning with global eco-conscious practices and economic growth within the context of environmental stewardship and sustainable development. However, the research acknowledges limitations related to the indirect measurement of decision-makers' psychological behavioral coefficients and the focus on efficiency metrics without extensive exploration of cultural, political, or legal factors. This work sets a new precedent in sustainable logistics research, encouraging future studies to incorporate direct behavioral data and qualitative factors for a more enriched evaluation. Its innovative approach not only contributes to the academic discourse on sustainable logistics but also offers practical tools for enhancing the MSR's trade efficiency and sustainability.

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Introduction

Launched by China in 2013, the Belt and Road Initiative (BRI), or One Belt, One Road (OBOR), aims to enhance economic connectivity and cooperation across Asia, Europe, Africa, and parts of South America through two main components: the Silk Road Economic Belt and the 21st Century Maritime Silk Road (Kuo and Kommenda, 2018; McBride et al., 2023). While the former focuses on land-based infrastructure and connectivity, including railways, highways, and pipelines to facilitate trade and cooperation across Eurasia, the latter is dedicated to developing maritime routes and port facilities to boost sea-based trade and connectivity, thus promoting efficient and secure maritime infrastructure (“China Global Investment Tracker”, 2023; Lam et al., 2018; Silin et al., 2018). These initiatives are part of China’s expansive strategy to revive and expand ancient trade routes, bolstering economic ties and reducing transportation costs through improved land and sea trade efficiency (Y. Huang, 2016; Ohashi, 2018).

The 21st Century Maritime Silk Road (MSR) specifically stands out for its critical role in reshaping global trade patterns, highlighting the importance of maritime trade and its impact on supply chains, economic growth in coastal regions, and environmental sustainability (Cigui, 2014; Jianren, 2016; Thorne and Spevack, 2017). It underscores the necessity for sustainable logistics in participating countries, which involves adopting eco-friendly transportation modes and practices to minimize ecological footprints and enhance transport efficiency. This is crucial for trade, economic growth, and the success of the MSR, as well as for fostering economic development and regional cooperation through improved connectivity (R. Liang and Liu, 2020; C. Wang et al., 2021; Zhong and Wu, 2020). Sustainable logistics supports environmental protection and responsible resource management, encourages innovation, and attracts international investment by aligning with global sustainability and social responsibility goals (Hu et al., 2022; C. Zheng et al., 2021). This approach is foundational to the MSR’s objectives, ensuring the resilience of supply chains and contributing to the broader ambitions of the BRI.

In this context, the integration of Data Envelopment Analysis (DEA) and Prospect Theory into a unified analytical framework represents a significant methodological advancement for evaluating the sustainability of logistics systems along the MSR. DEA, a robust quantitative modeling technique in operations research and management science, assesses the efficiency of decision-making units (DMUs), such as firms, organizations, or countries, by analyzing their input-output relationships (Charnes et al., 1978). Concurrently, Prospect Theory, developed by Daniel Kahneman and Amos Tversky in 1979, delves into the complexities of decision-making under risk and uncertainty (Kahneman, 1979). It challenges the traditional assumptions of rational expected utility theory, proposing instead that individuals make decisions based on outcomes relative to a reference point, with a differentiated sensitivity to losses and gains (Tversky and Kahneman, 1992). This methodological innovation marries DEA’s capacity to evaluate relative efficiency with the behavioral insights of Prospect Theory, crafting a comprehensive approach ideally suited for scrutinizing the sustainability of logistics systems along the MSR. Such a holistic evaluation framework is pivotal in aligning with the BRI’s strategic objectives, especially in promoting efficient, secure, and environmentally sustainable maritime trade routes.

This research aims to evaluate the sustainable logistics potential of countries strategically positioned along the 21st Century Maritime Silk Road, with a specific focus on assessing their readiness in terms of various key indicators. These indicators relate to economic, environmental, infrastructure, governance, and innovation. To achieve this, the research will employ the

DEA model enhanced by applying the Prospect theory. This approach enables the exploration of not only objective performance metrics but also the behavioral aspects of decision-makers, allowing for a comprehensive evaluation of sustainable logistics potential in these crucial checkpoint nations. Through this multifaceted assessment, the research seeks to provide valuable insights into how these countries can enhance their logistics capabilities in alignment with sustainability principles and efficient resource management along the Maritime Silk Road.

This approach fills existing research gaps by blending quantitative analysis with behavioral insights. It offers actionable guidance for enhancing sustainable trade practices within the Belt and Road Initiative (BRI) framework. These contributions offer a new dimension to logistics and sustainability studies, enhancing understanding of the MSR’s impact on global sustainable development.

The research consists of five chapters. Section “Introduction” introduces the topic. Section “Literature review” reviews relevant literature. Section “Methodology” explains the methodology, emphasizing DEA with prospect theory. Section “Numerical results” presents numerical results assessing countries’ efficiency along MSR. Section “Conclusion” concludes the study, summarizing findings and suggesting future research.

Literature review

BRI has become a focal point for many scholarly investigations, shedding light on its strategic, economic, and geopolitical underpinnings. Research in this area spans a broad spectrum, from examining the intricate economic and political landscapes that support the BRI to delving into the specific logistics and operational nuances of the MSR, a vital component of the initiative.

BRI impact analysis. The extensive studies on the BRI delve deeply into the economic and strategic facets shaping China’s engagements with partner countries. A notable example is the 2022 study by Wei Hu and his team, which meticulously examines the geo-economic ties binding China with countries along the MSR. Utilizing social network analysis, this research highlights China’s expanding influence and the emergence of strategic nodes like China, Japan, and Singapore, illustrating the dynamic and evolving nature of these international economic relationships (Hu et al., 2022). Such insights bring to the forefront the intricate web of economic interactions fostered by the BRI, emphasizing the need for carefully crafted strategies and cooperative efforts sensitive to the nuanced dynamics at play.

Building upon this narrative, C. Wang et al.’s research takes a closer look at the sustainability of fifteen Chinese ports integral to the BRI’s framework (C. Wang et al., 2021). By evaluating these ports based on their capabilities for sustainable development, the study contributes valuable insights for strategic planning and forming alliances to construct an effective global transportation network in alignment with the BRI’s ambitions. This focus on port sustainability underscores its vital importance in augmenting the efficacy and durability of the initiative’s infrastructural endeavors.

In 2021, the investigation applied link prediction theory to formulate a strategy for prioritizing port investments in Southeast Asia by J. Zheng et al. (J. Zheng et al., 2022). This approach considers the economic and political connections linking the region with China and seeks to optimize investment decisions to enhance efficiency and sustainability. This strategic initiative underscores a commitment to fulfilling the BRI’s overarching objectives while catering to the specific requirements and

prospects of the Southeast Asian maritime domain, reinforcing the BRI's role in shaping a more connected and sustainable global trade infrastructure. On the other hand, Song and Fabinyi address a significant knowledge gap by offering a pivotal exploration of Chinese maritime investment within ASEAN countries, shedding light on the often-overlooked impact of the blue economy on coastal livelihoods (Song and Fabinyi, 2022). Their meticulous examination of Chinese investments within the MSR framework of the BRI brings into focus the complexities, challenges, and opportunities associated with China's involvement in sectors like fisheries, mariculture, and tourism. While these investments promise economic benefits, such as job opportunities, the study uncovers intricate issues related to the equitable distribution of these benefits among local communities, rendering it essential reading for policymakers and researchers vested in the dynamics of coastal economic development.

MSR logistics research. Parallel to the overarching discussions on the BRI, a focused body of research dedicated to the MSR explores this maritime corridor's logistical, operational, and supply chain aspects. The 2020 study by R. Liang and Z. Liu is particularly notable for investigating the impact of port infrastructure connectivity on logistics performance and, by extension, economic growth in countries along the MSR (R. Liang and Liu, 2020). Their research underscores logistics performance as a pivotal intermediary, indicating that enhanced port connectivity has significant, albeit indirect, benefits for economic growth. This underscores the intricate relationship between infrastructure development, logistics efficiency, and economic advancement within the MSR framework.

In a similar vein, M. Jiang et al. enrich our comprehension of supply chain risks specific to the MSR by leveraging fuzzy logic and evidential reasoning methodologies (Jiang et al., 2023). Concentrating on fuel prices as a significant risk factor, their findings provide crucial guidance for the development of safety and risk management strategies tailored to the MSR's unique challenges, highlighting the importance of adaptive strategies in the face of the unpredictable nature of maritime logistics.

Besides, the operational efficiency of MSR ports has attracted scholarly attention, as evidenced by Tianci Huang et al.'s research (T. Huang et al., 2021). Utilizing DEA, they evaluated the performance of crucial MSR ports, identifying high performers like Qingdao Port and pinpointing opportunities for improvement across the network. This evaluation is a benchmark for enhancing operational standards and achieving excellence in the MSR's port operations. In another study, Xinfang Zhang et al. provide a comprehensive understanding of the spatio-temporal transformations in container ports along the MSR from 2000 to 2019 (Zhang et al., 2023). Their findings illuminate a notable shift in the center of gravity within the port system, with Asia emerging as a prominent player, overshadowing Europe. The study identifies recurring cycles of decentralization and agglomeration, resulting in the formation of distinctive 'spindle' or 'olive' structures in the port network. Most notably, the MSR's influence on port economics is revealed, particularly in its positive impact on smaller and medium-sized port clusters. These insights are indispensable for shaping the MSR framework's port development strategies and investment decisions.

In 2021, Zhao et al.'s study on the evolving port network along the MSR, viewed through sustainable development, projects substantial network configuration shifts (Zhao et al., 2021). The anticipated ascendance of Southeast Asian and South Asian ports as central hubs marks a pivotal change in the maritime network's structure, driven by sustainability initiatives. This evolution points to a dynamic reorientation of the MSR's logistical

backbone, reinforcing the importance of sustainable practices in shaping the future of global maritime logistics. In 2023, Lang Xu and their research team explored the repercussions of the MSR on logistics development in economically developed coastal provinces of China (Xu et al., 2023). Extensively analyzing data spanning from 2000 to 2020, they quantify the profound influence of the initiative on logistics development and construct a complex network encompassing 31 provinces and regions. Their research underlines the initiative's role in catalyzing logistics growth in these coastal areas, yet it elucidates variations in the extent of development across regions, offering critical insights into how the MSR has reshaped the logistics landscape.

Despite the comprehensive insights provided by existing studies, there remains a notable gap in fully understanding the sustainable logistics potential of countries along the MSR. Specifically, the existing research predominantly focuses on economic growth, trade, port efficiency, and geo-economic relations, with less emphasis on a holistic evaluation of sustainability readiness across economic, energy and environmental, infrastructure and logistics, governance and stability, and innovation factors. Through the proposed multifaceted assessment, our research seeks to deliver valuable insights into how these nations can improve their logistics capabilities, aligning with sustainability principles and efficient resource management. This endeavor will contribute to the ongoing discourse on the MSR, offering actionable recommendations for enhancing the sustainability and efficiency of logistics operations along this vital trade corridor.

Methodology

Prospect theory. Prospect theory, a seminal contribution to behavioral economics, was introduced by Kahneman and Tversky in 1979 (Kahneman, 1979). Since its inception, it has become one of the most widely applied theories in the realm of behavioral decision-making, finding applications in a multitude of disciplines (H. Liang et al., 2018; L. Wang et al., 2017). This theory elucidates the intricate and often seemingly irrational aspects of human decision-making, shedding light on how individuals evaluate and respond to various scenarios. At its core, prospect theory is underpinned by three fundamental principles that are central to understanding behavioral decision-making:

- **Reference dependence:** According to this principle, individuals' perceptions of gains and losses are not absolute but rather depend on a reference point. In essence, their starting point or reference influences how one perceives an outcome as positive or negative.
- **Loss aversion:** A critical insight from prospect theory is the concept of loss aversion. It posits that individuals tend to be more sensitive to losses than to equivalent gains. In other words, the emotional impact of a loss is typically more significant than the corresponding gain.
- **Diminishing sensitivity:** Prospect theory introduces diminishing sensitivity, suggesting that individuals exhibit risk-seeking behavior when it comes to potential losses while being risk-averse when it comes to potential gains. As such, the utility gained from an incremental increase in wealth decreases as one's wealth grows, leading to distinct preferences for risk in different contexts.

These three principles collectively construct the prospective value function, which defines how individuals perceive and evaluate outcomes. This function is typically represented as an asymmetrical S-shaped curve, visually illustrating the interplay of these principles.

Reference dependence bifurcates the prospect value function into distinct loss and gain domains. Meanwhile, loss aversion is reflected in the discrepancy between the slopes of the gain and loss domains, with losses having a steeper slope due to greater sensitivity. Lastly, the diminishing sensitivity principle manifests in the convex shape of the prospect value function in the gain domain and its concave shape in the loss domain. Mathematically, the prospect value function is expressed as Eq. (2), where Δt represents the value of loss or gain relative to the reference point. The parameters γ , δ , and θ correspond to the gain-risk attitude, loss-risk attitude, and loss aversion of decision-makers, respectively. By employing these parameters, the equation provides a quantitative model for understanding how individuals' decisions are influenced by prospect theory, making it a powerful tool for comprehending and predicting human behavior in various decision-making contexts.

$$f(\Delta t) = \begin{cases} (\Delta t)^\gamma, & \forall \Delta t \geq 0; 0 < \gamma < 1 \\ -\theta(-\Delta t)^\delta, & \forall \Delta t < 0; 0 < \delta < 1 \end{cases} \quad (1)$$

Data Envelopment Analysis. DEA, a quantitative modeling technique used in operations research and management science, assesses the relative efficiency of DMUs, such as firms, organizations, or countries, based on their input-output relationships. This method, developed by Charnes, Cooper, and Rhodes in 1978, allows for comparing multiple entities by handling multiple inputs and outputs simultaneously, making it invaluable in cases where traditional performance metrics fall short (Charnes et al., 1978; Cook and Seiford, 2009). The versatility of DEA is evidenced by its applications across various fields, including finance, healthcare, education, and environmental management, showcasing its utility as a tool for efficiency analysis and decision-making. The evolution of DEA since its inception has seen significant milestones, notably the introduction of the BCC model by Banker, Charnes, and Cooper in 1984, which allows for variable returns to scale, and the development of super-efficiency analysis by Doyle and Green in 1994, which identifies DMUs performing beyond the benchmark of the most efficient ones (Banker et al., 1984; Doyle and Green, 1994). These advancements have enhanced DEA's capability to provide nuanced evaluations of performance and efficiency across a broad spectrum of industries and contexts.

The DEA framework, encompassing both CCR and BCC models, provides an invaluable tool for assessing the performance of a set of DMUs, where each DMU, represented as $i = 1 \dots i$, manages multiple inputs ($j = 1 \dots J$) to produce various outputs ($t = 1 \dots T$). The calculation of the technical efficiency (E_k) for each specific DMU (k th) involves the solution of the mathematical model (2) that considers the intricate relationships between inputs and outputs.

$$\text{maximize } E_k = \rho + \sum_{t=1}^T u_t m_{tk}$$

subject to

$$\begin{aligned} \sum_{j=1}^J v_j n_{jk} &= 1 \\ \rho + \sum_{t=1}^T u_t m_{ti} - \sum_{j=1}^J v_j n_{ji} &\leq 0 \quad i = 1, \dots, I \\ u_t, v_j &\geq 0, \rho \text{ is free} \quad j = 1, \dots, J; t = 1, \dots, T \end{aligned} \quad (2)$$

where u_t and v_j signify the weight assigned to the t th output and the j th input, respectively. These weights are pivotal as they represent the relative importance of each input and output in the efficiency assessment process. Additionally, the n_{ji} and m_{ti} values

hold significance, where n_{ji} denotes the value of the j th input for the i th DMU and m_{ti} signifies the value of the t th output for the same DMU. Besides, ρ represents a scalar by which the sum of the products of outputs and their respective weights is maximized, considering DMU being evaluated. These values provide the actual data for the inputs and outputs used in the efficiency calculation, making them the foundation upon which DEA evaluates the performance of DMUs. The goal of the DEA is to determine the effectiveness of each DMU. A DMU is considered effective when its technical efficiency (E_k) equals 1.

Risk-considering DEA model. Drawing on the fundamental principles of prospect theory, Chen et al. have introduced a novel and innovative approach in the realm of DEA, offering a fresh perspective on behavioral decision-making and its application in evaluating efficiency with risk-considering (Chen et al., 2019). This behavioral DEA model consists of several distinctive steps, each designed to encapsulate the cognitive dynamics observed in individuals when they make decisions under risk and uncertainty.

Step 1: Normalization of inputs and outputs. The first step in this novel approach entails the determination of the normalized values of inputs (x_{ji}) and outputs (y_{ij}), a process encapsulated by Eqs. (3) and (4). Normalization is a critical component, as it allows for a fair and equitable comparison of diverse decision-making units while accommodating the inherent biases and subjectivity associated with human decision-making.

$$x_{ji} = \frac{n_{ji}^{\max} - n_{ji}}{n_{ji}^{\max} - n_{ji}^{\min}} \quad i = 1, \dots, I; j = 1, \dots, J \quad (3)$$

$$y_{ti} = \frac{m_{ti} - m_{ti}^{\min}}{m_{ti}^{\max} - m_{ti}^{\min}} \quad i = 1, \dots, I; t = 1, \dots, T \quad (4)$$

Step 2: Identification of reference points. The model proceeds to identify both positive and negative reference points to incorporate the psychological elements brought to the fore by prospect theory. These reference points, as outlined in Eqs. (5) and (6), are pivotal to understanding how individuals perceive and react to gains and losses. They provide a frame of reference against which gains and losses are evaluated, mirroring the reference dependence principle of prospect theory.

The positive reference points (n_j^+ and m_t^+):

$$n_j^+ = \min_i(x_{ji}); m_t^+ = \max_i(y_{ti}) \quad (5)$$

The negative reference points (n_j^- and m_t^-):

$$n_j^- = \max_i(x_{ji}); m_t^- = \min_i(y_{ti}) \quad (6)$$

Step 3: Construction of the risk-considering DEA model. The risk-considering DEA model is crafted in the third and final step, as articulated in Eq. (7). This model effectively amalgamates the normalized values of inputs and outputs, the concept of reference points, and the principle of diminishing sensitivity, which characterizes the response to gains and losses. The parameter φ assumes a pivotal role within this construct, signifying the relative degree of importance placed on gains instead of losses. When φ takes a value of 0.5, it signifies an equitable balance, suggesting that decision-makers consider gains and losses equally important.

$$\begin{aligned} \text{maximize } Z &= \varphi \left(\rho + \sum_{t=1}^T u_{tk} (y_{tk} - m_t^-)^\gamma + \sum_{j=1}^J v_{jk} (n_j^- - x_{jk})^\gamma \right) \\ &\quad - (1 - \varphi) \left(\rho + \sum_{t=1}^T u_{tk} \theta (m_t^+ - y_{tk})^\delta + \sum_{j=1}^J v_{jk} \theta (x_{jk} - n_j^+)^\delta \right) \end{aligned}$$

subject to

$$\begin{aligned} \sum_{j=1}^J v_{jk} n_{jk} &= 1 \\ \rho + \sum_{t=1}^T u_{it} m_{it} - \sum_{j=1}^J v_{ji} n_{ji} &\leq 0 \quad i = 1, \dots, I \\ u_{it}, v_{ji} &\geq 0, \rho \text{ is free} \quad j = 1, \dots, J; t = 1, \dots, T; i = 1, \dots, I \end{aligned} \tag{7}$$

Numerical results

Key countries in MSR and indicators. As mentioned in the section “Introduction”, this study focuses on the sustainable logistics performance of countries participating in the MRS. However, MSR’s investment and influence in many aspects is very vast (McBride et al., 2023). Therefore, this study only aims to analyze and evaluate key countries considered checkpoints, including important ports and hubs of MSR (Hu et al., 2022). The list of these countries, considered DMUs, is presented in Table 1 and illustrated in Fig. 1.

To evaluate the efficiency of the investment and development process of the creator of the MSR idea, China, against other countries in many factors. This study considers China’s

cumulative investment and construction as inputs to the risk-considering DEA model. The efficiency of this investment process is higher when the investment and construction value is lower. The data for these two inputs is collected from the China Global Investment Tracker database, which is provided by the American Enterprise Institute (AEI) (“China Global Investment Tracker,” 2023). As shown in Fig. 2, Djibouti, strategically located at the Red Sea entrance, has received substantial construction investments, indicating the development of critical infrastructure. Integral to China’s European strategy, Greece has seen substantial investments in infrastructure and port acquisitions. India’s investments, on the other hand, appear more focused on the technology and manufacturing sectors. Indonesia emphasizes financial and service-oriented investments over significant construction projects. In Italy, China invests in ports and infrastructure, enhancing trade routes. Kenya receives substantial construction investments in transportation infrastructure, aligning with China’s regional connectivity goals. Malaysia’s industrial projects, ports, and railways investments bolster regional integration. Sri Lanka’s infrastructure projects, notably the Hambantota Port, have sparked discussions on debt and geopolitical influence. Vietnam receives relatively lower investments and construction projects, reflecting the complex interplay of political and historical factors.

To evaluate logistics sustainability, twenty-nine indicators are evaluated as outputs of the DEA model, as shown in Table 2. However, to make assessments in many different aspects, this study classifies the indicators into five groups, including Economic factors, Energy and environmental factors, Infrastructure and logistics factors, Governance and stability factors, and Innovation factors. These outputs are applied to the risk-considering DEA model separately from the abovementioned inputs. One thing worth mentioning is that some of the outputs are undesired outputs. In other words, the smaller their value, the higher the efficiency. Data for these indicators are collected from databases and reports of international organizations such as the International Monetary Fund (IMF) (Balance of Payments

Table 1 MSR’s key countries as DMUs.

No.	Country	Country code	Capital	Region
1	Djibouti	DJI	Djibouti City	the Horn of Africa
2	Greece	GRC	Athens	Southeastern Europe
3	India	IND	New Delhi	South Asia
4	Indonesia	IDN	Jakarta	Southeast Asia
5	Italy	ITA	Rome	Southern Europe
6	Kenya	KEN	Nairobi	East Africa
7	Malaysia	MYS	Kuala Lumpur	Southeast Asia
8	Sri Lanka	LKA	Colombo	South Asia
9	Vietnam	VNM	Hanoi	Southeast Asia

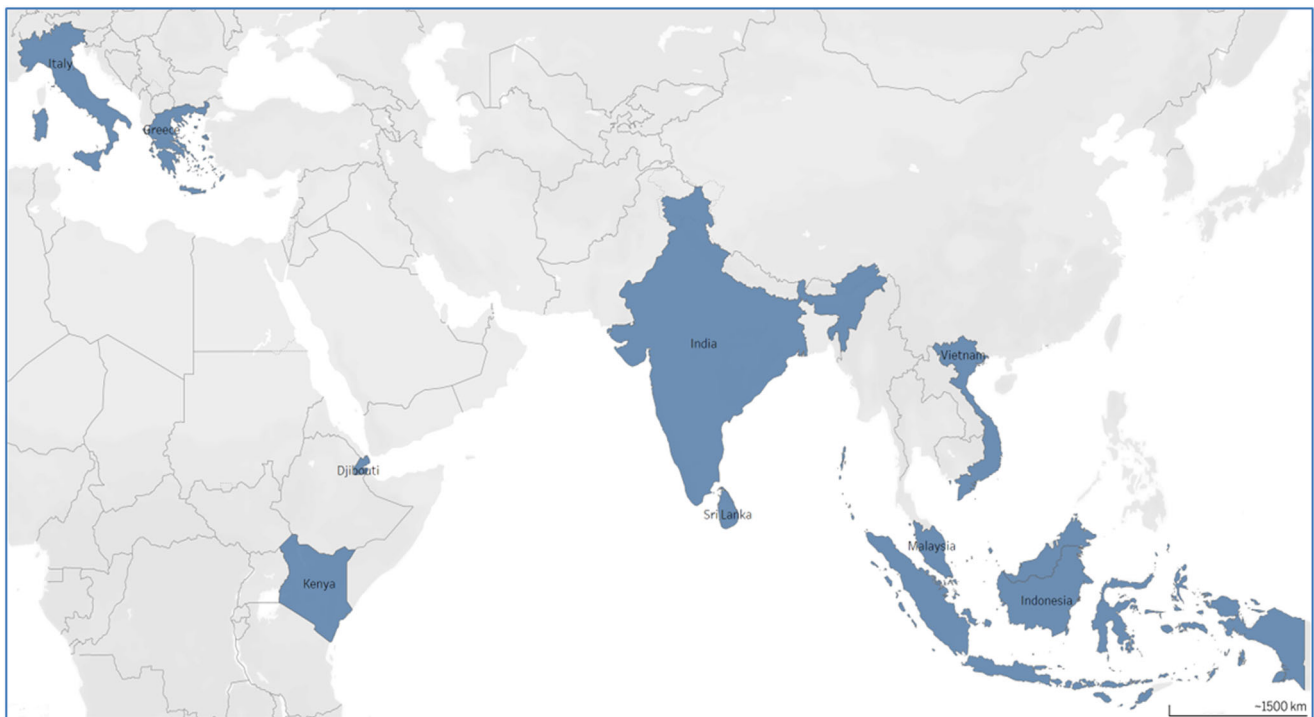


Fig. 1 MSR’s key checkpoint countries. The key checkpoint countries on the 21st Century Maritime Silk Road.

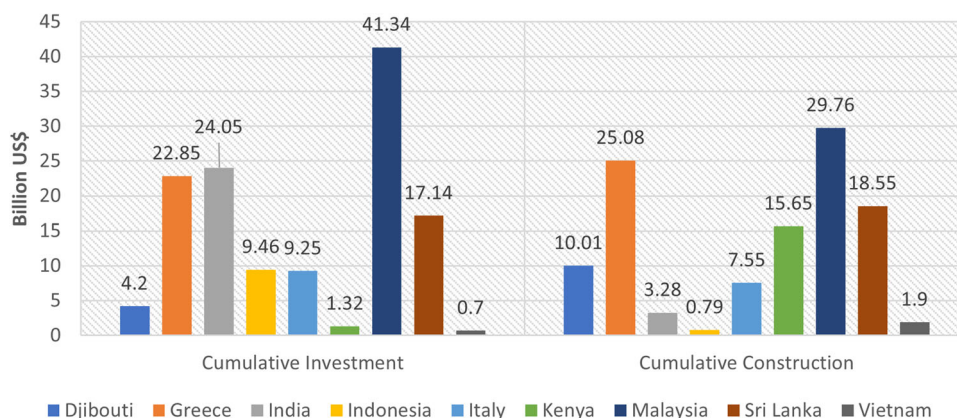


Fig. 2 China's cumulative investment and construction in 2023. The China's cumulative investment and construction in key checkpoint countries in 2023.

Table 2 List of economic factor outputs.			
Factor	Indicators	Measurement units	Undesired
Economic	Commercial service exports	Current Billion US\$	
	Commercial service imports	Current Billion US\$	
	Export value index	Score, 2015 = 100	
	Import value index	Score, 2015 = 100	
	GDP	Current Billion US\$	
	Inflation, GDP deflator	Annual %	X
	Merchandise trade	% of GDP	
Energy and environmental	Net trade in goods	Balance of Payments—BoP, current Billion US\$	
	The energy intensity level of primary energy	MJ/\$2017 PPP GDP	X
	Adjusted savings: carbon dioxide damage	Current Billion US\$	X
	Container port traffic	Thousand TEU: 20-foot equivalent units	X
Infrastructure and logistics	Cost to export, border compliance	US\$	X
	Cost to import, border compliance (US\$)	US\$	X
	Logistics performance index	Score, 1 = low to 5 = high	
	Machinery and transport equipment	% of value added in manufacturing	
	Time required to build a warehouse	Days	X
	Time to export, border compliance	Hours	X
	Time to export, documentary compliance	Hours	X
	Time to import, border compliance	Hours	X
	Time to import, documentary compliance	Hours	X
	Transport services	% of commercial service exports	
Governance and stability	Control of Corruption	Score	
	Government Effectiveness	Score	
	Political Stability and Absence of Violence/Terrorism	Score	
	Rule of Law	Score	
Innovation	Human capital index (HCI)	Score, scale 0-1	
	Industrial design applications, by count	Score	
	Patent applications	Count	

Statistics Yearbook, 2023; Regional Economic Outlook: Asia and Pacific, 2021; “World Economic Outlook Databases”, 2023), International Energy Agency (IEA) (IEA, 2022), United Nations Conference on Trade and Development (UNCTAD) (“UNCTAD Statistics”, 2023), Worldwide Governance Indicators (WGI) (Kaufmann and Kraay, 2023), the World Bank (“Business Ready (B-READY) database”, 2023; “World Bank Open Data.”), World Intellectual Property Organization (WIPO) (“Intellectual Property Statistics Data Center”, 2023), United Nations Industrial Development Organization (UNIDO) (United Nations Industrial Development Organization, 2023), Industrial Development Organization (IDO) (“Industrial Development Organization”, 2023), and World Trade Organization (WTO) (“WTO Stats”, 2023).

The Economic factor group includes indicators like commercial service exports, commercial service imports, Export Value Index, Import Value Index, Gross Domestic Product (GDP), and

inflation rates. These indicators provide insights into investment efficiency, with factors like GDP and trade balances affecting efficiency positively. The Energy and Environment factor includes three outputs: energy intensity, adjusted savings for carbon dioxide damage, and CO2 emissions. Energy intensity measures energy efficiency, with lower values indicating better efficiency. Adjusted savings for carbon dioxide damage represent the economic cost of emissions damage, and lower values suggest sustainable practices. CO2 emissions per capita indicate cleaner energy usage and environmentally conscious policies, reducing long-term risks and enhancing investment efficiency. The other group included indicators covering logistics and efficiency factors. Container Port Traffic reflects trade activity and efficient logistics, which can improve investment efficiency. Cost to Export and Cost to Import represent financial requirements for trade, lower costs benefit investment efficiency. The Logistics Performance Index assesses logistics efficiency, with higher

Table 3 Decision matrix of economic factor.

Indicators	Input/Output	Country								
		DJI	GRC	IND	IDN	ITA	KEN	MYS	LKA	VNM
Investment (Billion US\$)	Input	4.20	22.85	24.05	9.46	9.25	1.32	41.34	17.14	0.70
Construction (Billion US\$)	Input	10.01	25.08	3.28	0.79	7.55	15.65	29.76	18.55	1.90
Commercial service exports (Billion US\$)	Output	0.69	49.45	308.68	22.72	122.22	4.27	31.29	3.01	3.67
Commercial service imports (Billion US\$)	Output	0.58	29.24	175.86	43.34	132.33	3.80	41.55	2.15	19.41
Export value index (Score)	Output	2455.37	165.20	147.57	152.86	133.54	114.10	149.55	118.51	207.28
Import value index. (Score)	Output	460.72	162.13	145.36	137.39	135.68	121.54	135.24	108.99	200.22
GDP (Billion US\$)	Output	3.52	219.07	3385.09	1319.10	2010.43	113.42	406.31	74.40	408.80
Inflation, GDP deflator (annual %)	Output	1.20	8.11	8.32	9.57	3.01	6.01	6.46	48.85	3.86
Merchandise trade (% of GDP)	Output	283.01	70.80	34.77	40.14	66.97	25.67	159.22	42.20	178.73
Net trade in goods (Billion US\$)	Output	267.78	227.48	0.00	331.17	247.69	257.44	306.88	262.49	286.20

Table 4 Normalized decision matrix of economic factor.

Indicators	Input/Output	Country								
		DJI	GRC	IND	IDN	ITA	KEN	MYS	LKA	VNM
Investment	Input	0.914	0.455	0.425	0.784	0.790	0.985	0.000	0.595	1.000
Construction	Input	0.682	0.162	0.914	1.000	0.767	0.487	0.000	0.387	0.962
Commercial service exports	Output	0.000	0.158	1.000	0.072	0.395	0.012	0.099	0.008	0.010
Commercial service imports	Output	0.000	0.164	1.000	0.244	0.752	0.018	0.234	0.009	0.107
Export value index	Output	1.000	0.022	0.014	0.017	0.008	0.000	0.015	0.002	0.040
Import value index.	Output	1.000	0.151	0.103	0.081	0.076	0.036	0.075	0.000	0.259
GDP	Output	0.000	0.064	1.000	0.389	0.593	0.033	0.119	0.021	0.120
Inflation, GDP deflator	Output	1.000	0.855	0.851	0.824	0.962	0.899	0.890	0.000	0.944
Merchandise trade	Output	1.000	0.175	0.035	0.056	0.160	0.000	0.519	0.064	0.595
Net trade in goods	Output	0.809	0.687	0.000	1.000	0.748	0.777	0.927	0.793	0.864

scores indicating dependable supply chains and reduced risks and costs related to logistics issues. Indicators such as Machinery and Transport Equipment, Time Required to Build a Warehouse, and various time-related measures for border and documentary compliance impact a country’s trade efficiency, thereby influencing investment efficiency through streamlined processes and reduced costs, enhancing the business environment. The Control of Corruption, Government Effectiveness, Political Stability and Absence of Violence/Terrorism, and Rule of Law indicators collectively offer insights into a country’s governance and political stability, which are crucial for investment conditions. Higher scores in these indicators signify a more favorable and secure investment environment by reducing corruption, ensuring efficient government services, enhancing political stability, and strengthening legal frameworks. These factors collectively contribute to investment efficiency and security. In the last group, these indicators offer insights into a country’s innovation potential and the quality of its human capital, both critical factors for investment opportunities and economic development. The Human Capital Index (HCI) Score assesses a nation’s investment in education and skill development, enhancing investment efficiency with a more educated and skilled workforce. Industrial Design Applications, by Count, reflects creativity and innovation in product development, attracting investments and contributing to economic growth. Patent Applications indicate a commitment to innovation and intellectual property protection, fostering an environment that rewards innovation and encourages research and development investments.

Risk-considering DEA efficiency. In this section, the risk-considering DEA model (7) is applied to determine the efficiency

of DMUs. Their efficiency is determined separately for each factor mentioned above. In this study, in the first search for the solution, the values of the decision maker’s psychological behavioral coefficients, including the gain-risk attitude (γ), the loss-risk attitude (δ), the loss aversion (θ), and the gain-loss relative importance (ϕ) are used according to the findings in Amos Tversky and Daniel Kahneman’s research (Tversky and Kahneman, 1992). Specifically, the values of the gain-risk attitude, the loss-risk attitude, the loss aversion, and the gain-loss relative importance are 0.85, 0.92, 1.25, and 0.5, respectively. As the data collection process results, the economic factor decision matrix is presented in Table 3. According to the decision matrix, there seem to be significant differences in investment and construction spending. India stands out with the highest investment in China, at \$24.05 billion, while Greece leads in China’s construction spending, at \$25.08 billion. Next, the commercial service exports and imports reveal substantial variations. India dominates in both categories, exporting \$308.68 billion worth of services and importing \$175.86 billion. Export and import value index scores show that Djibouti has strong competitiveness in export and import markets, indicating a potentially favorable trade environment. GDP figures highlight India’s economic might with a GDP of \$3385.09 billion, while Djibouti has the smallest GDP at \$3.52 billion. Inflation rates vary, with Sri Lanka experiencing the highest at 48.85%. Meanwhile, merchandise trade as a percentage of GDP varies widely, with Djibouti at 283.01% and India at 34.77%. Net trade in goods is also noteworthy, with Indonesia having the highest surplus at \$331.17 billion. In the next step, the decision matrices are normalized according to Eqs. (3)–(4) in the section “Risk-considering DEA model”. As a result, the normalized decision matrix of economic factors is shown in Table 4. The normalization process is performed for all decision matrices

Table 5 Decision matrix of energy and environmental factor.

Indicators	Input/Output	Country								
		DJI	GRC	IND	IDN	ITA	KEN	MYS	LKA	VNM
Investment (Billion US\$)	Input	4.20	22.85	24.05	9.46	9.25	1.32	41.34	17.14	0.70
Construction (Billion US\$)	Input	10.01	25.08	3.28	0.79	7.55	15.65	29.76	18.55	1.90
The energy intensity level of primary energy (MJ/\$2017 PPP GDP)	Output	1.88	2.85	4.28	3.12	2.48	5.12	4.51	1.73	4.05
Adjusted savings: carbon dioxide damage (Billion US\$)	Output	0.02	2.47	95.81	24.54	11.89	0.84	9.53	0.94	12.38
CO2 emissions (metric tons per capita)	Output	0.39	4.77	1.58	2.07	4.73	0.37	7.38	1.00	3.68

Table 6 Decision matrix of infrastructure and logistics factor.

Indicators	Input/Output	Country								
		DJI	GRC	IND	IDN	ITA	KEN	MYS	LKA	VNM
Investment (Billion US\$)	Input	4.20	22.85	24.05	9.46	9.25	1.32	41.34	17.14	0.70
Construction (Billion US\$)	Input	10.01	25.08	3.28	0.79	7.55	15.65	29.76	18.55	1.90
Container port traffic (Million TEU: 20-foot equivalent units)	Output	0.692	6.079	19.94	11.80	11.30	1.44	28.26	7.25	18.36
Cost to export, border compliance (US\$)	Output	605.29	300.00	211.92	211.07	0.10	142.50	212.50	366.11	290.00
Cost to import, border compliance (US\$)	Output	1055.00	0	266.11	382.59	0.10	832.50	212.50	299.67	373.00
Logistics performance index (1 = low to 5 = high)	Output	2.70	3.70	3.40	3.00	3.70	2.70	3.60	2.80	3.30
Machinery and transport equipment (% of value added in manufacturing)	Output	1.50	9.63	20.74	13.44	29.28	4.10	32.33	1.50	31.69
Time required to build a warehouse (days)	Output	146.00	180.00	106.22	200.13	189.50	159.00	41.00	86.00	166.00
Time to export, border compliance (hours)	Output	72.00	24.00	52.12	56.28	0	15.50	28.00	43.00	55.00
Time to export, documentary compliance (hours)	Output	60.00	1.00	11.64	61.32	0.50	19.00	10.00	48.00	50.00
Time to import, border compliance (hours)	Output	118.00	0.50	65.30	99.36	0	194.00	36.00	72.00	56.00
Time to import, documentary compliance (hours)	Output	50.00	0.50	19.88	106.22	0.50	60.00	6.50	48.00	76.00
Transport services (% of commercial service exports)	Output	82.74	49.81	12.16	20.75	11.51	38.52	18.53	39.01	11.51

below. For energy and environmental factors, as shown in Table 5, The energy intensity level of primary energy data showcases the energy efficiency of these economies, with Djibouti and Sri Lanka demonstrating the highest efficiency. These countries generate more economic output per unit of energy consumed, reflecting sustainable energy practices. Besides, India incurs a significant \$95.81 billion in damage, underlining the financial impact of emissions. In contrast, Djibouti's damage is relatively minor at \$0.02 billion. Lastly, Greece records the highest emissions per capita at 4.77 metric tons, while Djibouti's footprint is the smallest at 0.39 metric tons, suggesting more environmentally sustainable practices.

The decision matrix is shown in Table 6, considering infrastructure and logistics factors. According to the data, the Container Port Traffic data reveals Malaysia's prominence with the highest container port traffic at 28.26 million TEU, followed by India at 19.94 million TEU, signifying their robust international trade activities. The Cost to Export and Import, Border Compliance indicators showcase the expenses of complying with export and import regulations at national borders. Djibouti faces the highest export border compliance cost at \$605.29, while Italy boasts the lowest at \$0. These figures highlight the differences in the efficiency of export and import processes, with lower costs indicating smoother and more cost-effective procedures. The Logistics Performance Index assesses overall logistics efficiency. Greece stands out with a high score of 3.70, indicating superior logistics performance, while Djibouti scores lower at 2.70, suggesting a less efficient logistics environment. The Machinery

and Transport Equipment percentage in Value Added Manufacturing reveals Italy's significant reliance on machinery, comprising 29.28% of its manufacturing value added. In comparison, Djibouti has the lowest percentage at 1.50%, reflecting diverse manufacturing profiles. Additional indicators like the Time Required to Build a Warehouse and various time-related aspects of border compliance, both for exports and imports, provide insights into the time efficiency of these processes. Italy seems to excel with a short 41 days for warehouse construction, while Djibouti stands out with a mere 0.10 h required for export border compliance. Lastly, the Transport Services as a Percentage of Commercial Service Exports illustrates Djibouti's dominance with 82.74%, underscoring the importance of its transport services sector.

About governance and stability, as shown in Table 7, India shows a solid score of 308.68, while Italy and Greece lag, suggesting room for improvement in addressing corruption. Regarding Government Effectiveness, India again leads with a high score of 175.86, reflecting efficient government operations. In contrast, Italy and India have relatively lower scores, indicating less effective governance. Regarding Political Stability and the Absence of Violence or Terrorism, Djibouti shines robustly at 2455.37, signaling a secure and stable political environment. At the same time, Italy and Kenya exhibit lower scores, suggesting potential instability. Lastly, the Rule of Law, which evaluates a country's adherence to the rule of law, finds Djibouti excelling with a score of 460.72,

Table 7 Decision matrix of governance and stability factor.

Indicators	Input/ Output	Country								
		DJI	GRC	IND	IDN	ITA	KEN	MYS	LKA	VNM
Investment (Billion US\$)	Input	4.20	22.85	24.05	9.46	9.25	1.32	41.34	17.14	0.70
Construction (Billion US\$)	Input	10.01	25.08	3.28	0.79	7.55	15.65	29.76	18.55	1.90
Control of Corruption (Score)	Output	0.69	49.45	308.68	22.72	122.22	4.27	31.29	3.01	3.67
Government Effectiveness (Score)	Output	0.58	29.24	175.86	43.34	132.33	3.80	41.55	2.15	19.41
Political Stability and Absence of Violence/ Terrorism (Score)	Output	2455.37	165.20	147.57	152.86	133.54	114.10	149.55	118.51	207.28
Rule of Law (Score)	Output	460.72	162.13	145.36	137.39	135.68	121.54	135.24	108.99	200.22

Table 8 Decision matrix of innovation factor.

Indicators	Input/ Output	Country								
		DJI	GRC	IND	IDN	ITA	KEN	MYS	LKA	VNM
Investment (Billion US\$)	Input	4.20	22.85	24.05	9.46	9.25	1.32	41.34	17.14	0.70
Construction (Billion US\$)	Input	10.01	25.08	3.28	0.79	7.55	15.65	29.76	18.55	1.90
Human capital index (HCI) (scale 0-1)	Output	0.49	0.69	0.49	0.54	0.73	0.55	0.61	0.60	0.69
Industrial design applications (by count)	Output	165	1205	13723	2668	31112	165	1904	546	4387
Patent applications (by count)	Output	13	926	61573	8800	11078	197	7534	539	8534

Table 9 Risk-considering DEA model results.

Country	Economic efficiency	Energy and environmental efficiency	Infrastructure and logistics efficiency	Governance and stability efficiency	Innovation efficiency
Djibouti	0.783	1.000	0.578	0.576	0.564
Greece	0.633	0.707	1.000	0.613	0.818
India	0.621	0.697	0.625	0.603	0.598
Indonesia	0.577	0.616	0.562	0.561	0.549
Italy	0.635	0.610	1.000	0.561	0.890
Kenya	0.629	1.000	0.606	0.598	0.593
Malaysia	0.645	0.637	0.670	0.617	0.617
Sri Lanka	0.604	0.864	0.605	0.604	0.600
Vietnam	0.355	0.313	0.307	0.299	0.430

indicating a robust legal framework. At the same time, Greece and Italy show lower scores, indicating room for improvement.

For the innovation factor, The HCI, measured on a scale from 0 to 1, reflects the quality of a nation’s workforce, with Italy notably leading with a high score of 308.68. At the same time, India and Djibouti have room for improvement, as shown in Table 8. Industrial Design Applications demonstrate robust design and product innovation activity in Italy and India. Regarding intellectual property creation, Italy stands out with a substantial count of 11,078 patent applications, emphasizing a robust culture of innovation.

As the concluding phase of the proposed methodology, this study implements the risk-considering DEA model, denoted as the model (7), to comprehensively evaluate the efficiency of countries. This evaluation is performed by leveraging decision matrices and normalized decision matrices, which are processed and analyzed through the Lingo 11 Solver, a robust computational tool for optimization. This step is pivotal as it enables a holistic assessment of efficiency that considers the complexities of decision-making processes, particularly in scenarios characterized by risks and uncertainties. The risk-considering DEA model’s results are summarized and shown in Table 9 below.

Based on the results of the risk-considering model, illustrated in Fig. 3, several insights can be discerned. Despite areas where it can improve, Vietnam stands out for its cost-effective economic

efficiency, making it a pivotal player in facilitating affordable maritime trade and transportation activities. This characteristic enhances the success of the 21st Century Maritime Silk Road as it ensures cost-efficient and streamlined trade operations in the region. Indonesia’s high efficiency in energy and environmental factors aligns well with the sustainability goals of the Maritime Silk Road. Its efficient governance and stability factors contribute to a secure investment environment and economic and logistics efficiency improvements can further enhance its role as a crucial maritime checkpoint. Malaysia’s balanced efficiency is vital as a strategic maritime checkpoint. This balance ensures that it can effectively facilitate connectivity and trade along the Maritime Silk Road, thereby playing a crucial role in the economic and logistical aspects of the trade route.

In South Asia, India’s balanced efficiency across multiple factors underlines its significance in the Maritime Silk Road. The efficient governance and stability factors are paramount for ensuring the smooth and secure operation of maritime activities, while its demonstrated potential in innovation positions it as a promising partner for technology and trade-related initiatives along this maritime route. Sri Lanka’s efficiency in energy and environmental factors is significant for implementing eco-friendly maritime projects along the Maritime Silk Road. Its demonstrated stability, combined with efficiency in economic and infrastructure aspects, makes it a notable checkpoint on this maritime route.

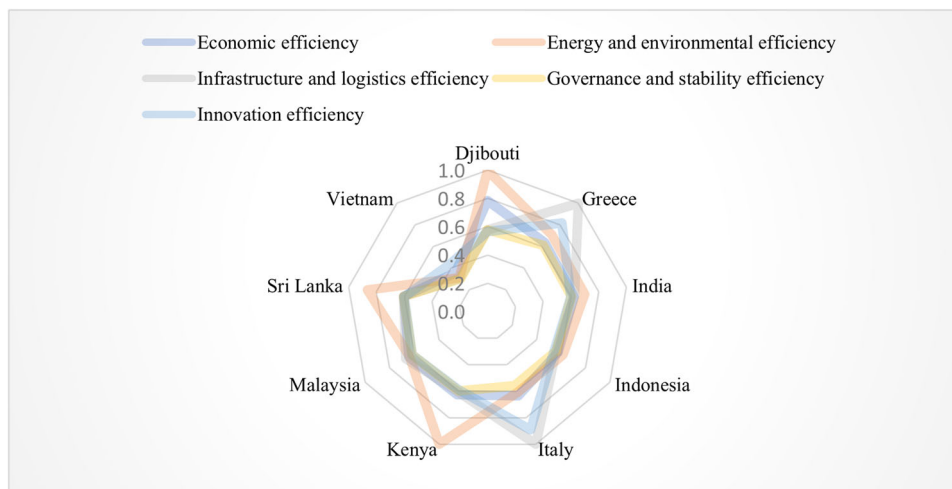


Fig. 3 Comprehensive efficiency of key checkpoint countries in MSR. The comprehensive efficiency of key checkpoint countries in MSR by the proposed approach.

In Europe, Greece, on the other hand, is a standout checkpoint with the highest efficiency in infrastructure and logistics. This underscores its pivotal role in ensuring the seamless flow of goods and services along the maritime route. The high efficiency in innovation factors also highlights its potential for technology-driven collaborations, positioning it as a hub for innovation and trade. Despite this, there's room for improvement in other areas, such as the economic factor, to bolster its overall attractiveness as a maritime checkpoint. Italy's efficiency in infrastructure and logistics factors is essential for its role in the 21st Century Maritime Silk Road, notably its strategic location in the Mediterranean. Moreover, investments in ports and high-tech sectors further strengthen its position as a maritime hub.

Lastly, in Africa, Djibouti, with its impressive efficiency in energy and environmental factors, indicates a commitment to sustainability, a crucial aspect for preserving the environment along the Maritime Silk Road. Furthermore, its strong efficiency in economics, governance, and stability factors suggests a conducive environment for investment and secure operations. Djibouti's significance in the region's strategic location is complemented by its efforts towards sustainability, making it a crucial hub. Kenya's high efficiency in energy and environmental factors is critical for ensuring that environmentally conscious initiatives along the Maritime Silk Road are successful. The country's overall strong efficiency in various other areas further enhances its significance as a crucial maritime checkpoint.

The analysis of the risk-considering model reveals a multifaceted landscape of efficiencies and strategic roles among countries along the 21st Century Maritime Silk Road. Key findings highlight Vietnam's cost efficiency, Indonesia's sustainability alignment, and the balanced efficiency of Malaysia, India, and Sri Lanka, each contributing uniquely to the initiative's success. European checkpoints like Greece and Italy and African hubs such as Djibouti and Kenya underscore the global span of the Maritime Silk Road's influence, emphasizing the importance of infrastructure, innovation, and sustainability. These insights underscore the necessity for targeted improvements and collaborative efforts to enhance the Maritime Silk Road's overall effectiveness, sustainability, and economic impact.

Conclusion

In this research, we explored the sustainable logistics potential of strategically positioned countries along the MSR, an integral

component of the BRI. By employing a specialized DEA model that innovatively incorporates risk considerations, including the nuanced behavioral aspects of decision-making, we meticulously assessed key indicators spanning economic performance, energy efficiency, infrastructure robustness, governance quality, and innovation capabilities.

Our analysis highlighted several countries' distinctive logistics potential, underscoring Vietnam's exceptional, cost-effective economic efficiency and Indonesia's standout performance in sustainability and governance. Malaysia's portrayal of balanced efficiency emerged as a cornerstone for facilitating seamless trade flow. Furthermore, countries like India, Greece, Djibouti, and Kenya were identified as possessing strong suits in diverse factors, positioning them as indispensable partners in the MSR framework. Notably, the comprehensive evaluation extended by our research sheds valuable light on the multifaceted logistics capabilities and potential areas for growth among these nations, marking them as pivotal contributors to the MSR's success.

The core contribution of our study lies in its innovative application of a risk-aware DEA model, marking a significant advancement in the assessment methodologies traditionally employed for evaluating sustainable logistics potential. This model's novelty is accentuated by incorporating Prospect Theory to account for risk considerations and behavioral aspects, a feature scarcely explored in existing logistics research. This approach enhances the robustness of our evaluation and introduces a nuanced lens through which the sustainable logistics potential of MSR countries can be appraised. By bridging the gap between quantitative analysis and qualitative behavioral insights, our research offers a more holistic understanding of the dynamics in shaping sustainable logistics practices along the MSR.

Furthermore, our study stands out for its novel integration of behavioral factors into the logistical assessment framework, a pioneering step that provides invaluable insights for policymakers, investors, and business leaders. This comprehensive assessment tool guides strategic decision-making, promoting sustainability in MSR trade activities. It aligns with global eco-conscious practices and aims to catalyze economic growth within environmental stewardship and sustainable development.

Despite its impactful contributions, our research acknowledges the limitation inherent in the indirect measurement of

decision-makers' psychological behavioral coefficients, a challenge stemming from integrating Prospect Theory within the DEA model. This limitation highlights the model's reliance on subjective judgments and behavioral preferences, which, while innovative, calls for future explorations to refine and enhance the accuracy of sustainable logistics assessments. Additionally, the focus on efficiency metrics without delving into the cultural, political, or legal factors that also significantly influence logistics capabilities underscores an area for further research. Future studies are encouraged to collect and incorporate behavioral data, alongside qualitative and behavioral factors, to offer a more enriched and comprehensive evaluation of sustainable logistics potential along the 21st Century Maritime Silk Road, thus expanding the horizons of this pioneering research.

Data availability

All data generated or analyzed during this study are included in this published article.

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Author contributions

C-NW: methodology, supervision, validation, funding acquisition, writing—review, and editing. N-LN: conceptualization, methodology, analysis, validation, writing—review & editing. C-MC: conceptualization, methodology, analysis, writing—original draft.

Competing interests

The authors declare no competing interests.

Ethical approval

This article does not contain any studies with human participants performed by any of the authors.

Informed consent

This article does not contain any studies with human participants performed by any of the authors.

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