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Disentangling the resiliency of international transportation systems under uncertainty by a novel multi-layer spherical fuzzy decision-making framework: Evidence from an emerging economy

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ABSTRACT

Although transportation systems play a critical role in the global socio-economic facets, they are acknowledged as vulnerable systems directly impacted by unexpected events, e.g., natural calamities, war, traffic accidents, terrorist attacks, and public health. In this respect, improving the resiliency of transportation systems under uncertainty is a controversial global challenge that this study could underpin. To do so, a systematic literature review (SLR) extracted a list of resiliency factors for resilient transportation systems. Next, a novel version of spherical fuzzy Delphi (SFD) screened factors, considering the case of Iran's international maritime transportation system. Moreover, the causal network relationship of the finalised factors was analysed by a novel hybrid spherical fuzzy approach, including a decision-making trial and evaluation laboratory (DEMATEL) and the analytic network process (ANP). Later, the unexpected events that occurred after 2000 were investigated. The SLR deeply investigated 51 of the top relevant articles. As a result, 12 factors and 22 subfactors that affect transportation systems resiliency were extracted. Notably, the rest of the findings primarily apply to the Iranian context. By implementing the SFD, ten factors were screened for Iran's international maritime transportation system and then analysed by SF-DEMATEL. After, the analysed factors were weighted by SFANP, where "recoverability" was selected as the most critical factor, and the "technological and communicational" factor was chosen as the least critical factor. Furthermore, the results provide a critical analysis of the policies adopted by Iran's international maritime transportation system to enhance resiliency under disruptive events.

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1. Introduction

Transportation systems champion the flourishing of global socio-economic (European Commission, 2023; Wang et al., 2023; Yin et al., 2023). In this vein, the European Commission confirmed the direct role of the transportation section in employing about 10 million workers and growing 10 % of the GDP (European Commission, 2023). This contribution is 5 % of the GDP and 17 million job opportunities in Asia (Begawan, 2021). Above all, maritime transportation is liable for over 80 % of the volume of international trade (UNCTAD, 2022; Gu & Liu, 2023). This percentage is even higher in most developing countries like Iran, with 90 % (Akbulaev & Bayramli, 2020). Globally, maritime transportation is the backbone of trade, economy, and international relations (UNCTAD, 2022). In a world of uncertainty, such systems must rapidly recover from such disturbances to avoid detriments (Gu & Liu, 2023). Though maritime transportation infrastructure has progressed, it is still vulnerable (Chen et al., 2018; Dui et al., 2021; Notteboom et al., 2021; Gu & Liu, 2023). It has been endangered by several unexpected events (e.g., weather events, conflicts, health crises, accidents) that drastically disrupt its demand–supply cycle (Dui et al., 2021; Gu & Liu, 2023). For instance, the COVID-19 pandemic, the Russia-Ukraine conflict, and storms have initially hit maritime transport and logistics, blunting some ports and blocking others, deviating sea routes, prolonging delays, and raising costs. Subsequently, applicants were left without suppliers and missed vital goods, prices were ramped up for end consumers, and a recession occurred (UNCTAD, 2022).

Ergo, resiliency in maritime transportation systems must be enhanced globally to face the worsening increasing disasters predicted due to ongoing climate change, conflicts, etc. (UNCTAD, 2022; Gu & Liu, 2023). This issue has received great attention from researchers, practitioners, and policymakers (Gu & Liu, 2023). Practically, $37 billion per annum (from 2015 to 2030) has been allocated to transportation systems in Asia's low-income regions to adapt to climate change, improve infrastructures, and repair plans (Asian Development Bank, 2022). Academically, apart from several articles that studied transportation system resiliency from different perspectives, researching this theme is still in urgent demand (Chen et al., 2018; Dui et al., 2021; Notteboom et al., 2021; Gu & Liu, 2023). One of the missing issues in the existing literature is identifying and ranking resilience factors of the international maritime transportation system and analysing their cause-and-effect interactions by a mixed-method approach (Nipa & Kermanshachi, 2021; Serdar et al., 2022). The high-level concern is improving global transportation systems resiliency (Serdar et al., 2022). Global and international refer to worldwide issues, not just a specific country. However, 'global' investigates world concerns, whereas 'international' is used when considering two or more countries. Hence, improving international transportation systems' resiliency must occur in advance to reach a progressed, resilient global one. Moreover, quantitatively investigating the impacts of a wide range of unexpected events on such finalised factors is another obligation (Gu et al., 2020; Notteboom et al., 2021) so that appropriate policies can be implemented to underpin a resilient international maritime transportation system (UNCTAD, 2022).

Accordingly, this paper pursues two main objectives. **(RO_1)** Identifying and prioritising the resiliency factors for the international maritime transportation system and designing its causal network framework. **(RO_2)** Investigating the impacts of adopted policies under a wide collection of events over two past decades on the extracted factors considering the maritime transportation of the emerging economy of Iran. First, an SLR has been employed to extract such factors to accomplish this feat. Afterwards, a novel version of SFD was developed to screen the extracted factors, considering the case of Iran's international maritime transportation system. Then, the priority and causal relationships of the finalised factors were analysed by a novel hybrid spherical fuzzy DEMATEL and ANP (SFDANP) approach. Later, the unexpected events that occurred after 2000 have been extracted and classified. Later, a decision-making matrix investigated the impacts of policies adopted by an emerging economy under such events on the screened and weighted resiliency factors. The results provided an evaluation of the policies adopted by Iran to enhance the resiliency of the international maritime transportation system even under uphill disasters for an emerging economy.

The paper is organised as follows. The extant literature is systematically reviewed in Section 2. Section 3 explains the research methodology framework, including the survey scheme, data collection, and analysis methods (i.e., SFD and SFDANP). Findings are reported in Section 4. The theoretical, practical, and managerial implications are discussed in Section 5. Eventually, the conclusion, research limitations, and future recommendations are presented in Section 6.

2. Literature review

"The word resilience emanates from the Latin word 'Resiliere' meaning jump back" (Zhou et al., 2019). Professionally, it was initially conceptualised in the ecological field by Holling (1973), then launched into various sciences, e.g., engineering, social, and economics (Zhou et al., 2019; Gu & Liu, 2023). Apart from differentiations, it is unanimous that resiliency is the system's capability to swiftly rebalance after perturbation (Zhou et al., 2019). The resiliency of transportation systems has been mainly controversial due to recent natural and artificial disasters (Zhou et al., 2019; Gu & Liu, 2023; Yin et al., 2023). Interestingly, the definition of resilience was distinguished for each transportation system mode in the extant literature (please see Zhou et al. (2019) to access a collection of them). For convenience, a routine meaning of transportation systems resilience was considered in this paper. This means the system can proactively gird for, withstand, and become attuned to the crisis by rapidly responding to and recovering from disruption. A popular diagram of resilient transportation systems is demonstrated in Fig. 1, via which resilience dimensions were distinguished before, during, and after an unexpected event (e.g., Zhou et al., 2019; Gu & Liu, 2023; Yin et al., 2023).

According to the resilience triangle proposed by Bruneau et al. (2003), In the ex-ante preparation stage, the performance level of a transportation system is high and undisrupted. However, it must proactively guard against such unexpected events by anticipating, monitoring, learning, etc. The transportation system's reliability is an appropriate indicator of these capabilities. Moreover, its redundancy becomes important near the second stage. When a perturbation occurs, this system must be agile to swiftly respond to and recover from such disruptions. However, its vulnerability negatively impacts responsiveness and recoverability.

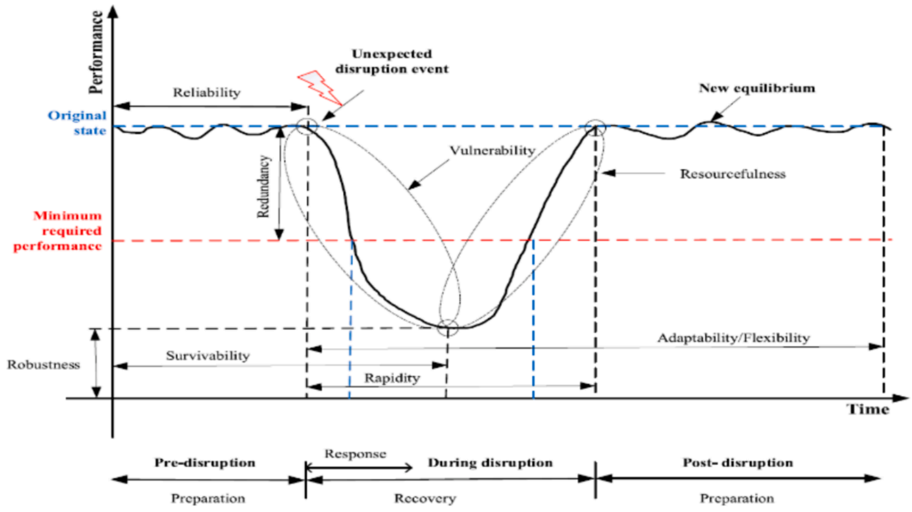

Fig. 1. Diagram of resiliency dimensions of transportation systems (Gu & Liu, 2023).

Nonetheless, vulnerability (susceptibility to damage or perturbation) can be diminished by improving the robustness of the transportation systems (Gu & Liu, 2023; Yin et al., 2023). Indeed, vulnerability indicates the network's opposition to the expansion of failure associated with connectivity, capacity and accessibility (Serdar et al., 2022). Resourcefulness is essential to compensate for the lowest performance results from disruption and reach a new balance point. In an ex-post preparation stage, system adaptability and flexibility are mainly highlighted to maintain the new high-level performance, which may be equal to the recent one. Therefore, flexibility even leads to benefits from turbulence in a new composure.

Underpinning a resilient transportation system (RTS) has been a vital ambition in a world of uncertainty (Yin et al., 2023). To prove this context, a three-stage protocol of Scientific Procedures and Rationales for Systematic Literature Reviews (SPAR-4-SLR) was applied to review the extant literature systematically (Paul et al., 2021). Firstly, eight criteria were considered: research required input and scope, source type, quality, language, search mechanism, period, and keyword. To this end, the resiliency factors (research input set) in international transportation systems under uncertainty (research scope) were extracted. As such, English review and research articles and chapters (type and language of source) listed in Scopus and Web of Science were mentioned, particularly those belonging to five valid and popular databases Elsevier, Springer, Taylor & Francis, Wiley, and Emerald. These are appropriate in providing worthwhile information for investigating articles, like year, country, and type of article (Paul et al., 2021). After carefully considering the extant literature, we identified Scopus and Web of Science as our primary bibliometric databases. While Google Scholar is another widely-used database, our decision was informed by previous research that compared the growth rate of publications, citations, and coverage of these major options. These studies revealed that all three databases exhibit consistent quarterly growth for publications and citations and can serve as viable alternative data sources (Harzing and Alakangas, 2016). Besides, Martín-Martín et al. (2018) argued that Google Scholar citation data is a superset of Web of Science and Scopus in all fields. However, its citation pool includes non-journal sources like books, conference papers, and unpublished materials, many of which are non-English and less cited than those in Scopus or Web of Science. Hence, we just focused solely on Scopus and Web of Science for the abovementioned reasons and the advanced filtering facilities they provide, allowing swift and easy access to the most critical and relevant works, particularly those in English and journals. Moreover, journals with an admissible grade according to the Australian Business Deans Council (ABDC) (source quality) were scrutinised. The prioritising indicators and techniques vary in institutions. This leads to various data. Hence, ABDC's confirmed reliability and popularity motivated the authors to employ it here (Paul et al., 2021).

Therefore, articles and chapters with titles, abstracts, and keywords pertinent to this research realm were sought, and 976 works were initially found (material acquisition). The distinguished sources were published from 2014 to 2023 (search period) with attached keywords (search keywords) such as *"resiliency factor of international transportation systems under uncertainty"*, *"resilience transportation network (or system)"*, *"resilience international transportation system"*, *"transportation system resilience"*, *"resilience in transportation systems"*, *"resilience of transportation systems"*, etc. To ensure the most accurate results, the search was formulated as:'TITLE-ABS-KEY (("*Resilience factors of*" OR "*Resilience*" OR "*Resilience in*" OR "*Resilience of*") AND ("*Transportation systems*" OR "*Transportation networks*" OR "*International transportation systems*" OR "*International transportation systems*")) AND (DOCTYPE (ar) AND NOT DOCTYPE (bk) AND NOT DOCTYPE (cp) AND NOT DOCTYPE (ed)) AND (LANG(English)) AND (PUBYEAR AFT 2014 AND PUBYEAR BEF 2023)'. Secondly, 49 items, including articles, conference papers, and book chapters, were found to be duplicated, and they were eliminated. Next, the filters above were applied to 927 tracks. Thus, 872 of their irrelevant points were ignored. As a result of the depth scan, viz., fully reading 55 relevant studies' titles and abstracts, four papers were considered irrelevant. For instance, two sample sources (one included and one excluded paper) were illustrated in Table 1 to clarify how the selection criteria were operationalised in practice.

As demonstrated, although (Bao and Zhang, 2018) are relevant to our research scope, it does not provide relevant input for this research, i.e., resiliency factors of transportation systems. Therefore, it was excluded from this paper dataset after the depth scan.

Table 1
Sample of included and excluded sources.

Selection Criteria **Sample Source**	**Research input and scope:** The resiliency factors in international transportation systems under uncertainty	**Source type:** Journal research and review articles and chapters	**Source language:** English	**Source quality:** ABDC	**Search mechanism:** Scopus and Web of Science (Elsevier, Springer, Taylor & Francis, Wiley, and Emerald)	**Search period:** 2014 to 2023	**Keyword:**((“Resilience factors of” OR “Resilience” OR “Resilience in” OR “Resilience of”) AND (“Transportation systems” OR “Transportation networks” OR “International transportation systems” OR “International transportation systems”))
Included source: Gu, B., & Liu, J. (2023). A systematic review of resilience in the maritime transport. *International Journal of Logistics Research and Applications*, 1–22.	✓	✓	✓	✓	✓	✓	✓
Excluded source: Bao, D., & Zhang, X. (2018). Measurement methods and influencing mechanisms for the resilience of large airports under emergency events. *Transportmetrica A: Transport Science*, *14*(10), 855–880.	✗	✓	✓	✓	✓	✓	✓

Nonetheless, (Gu and Liu, 2023) were confirmed by all selection criteria; thus, it was included in our data source. Hence, the dataset of this study was completed with 51 sources. From the final selected references, 29.4 % were review studies, and 70.6 % were research articles. Moreover, 28 journals were labelled applicable. The first three journals with the highest relevant publications (22.9 %, 10.4 %, and 6.3 %) were *Transportation Research Part A: Policy and Practice, Reliability Engineering & System Safety, and Transport Policy*, respectively. Consequently, the concise results from carefully reviewing 51 considered studies are provided in Table 2.

To our knowledge, the extant relevant literature can be divided into seven categories based on their main contribution. (i) Presenting a state-of-the-art comprehension of RTS (17.3 %) (e.g., Pan et al., 2021; Gu & Liu, 2023). (ii) Exploring indicators and strategies toward an RTS (15.4 %) (e.g., Nipa & Kermanshachi, 2021; Serdar et al., 2022). (iii) Investigating the impacts of catastrophic events/disasters on transportation system resiliency and/or assessing the performance of its infrastructure under such uncertainties (9.6 %) (e.g., Gu et al., 2020; Notteboom et al., 2021). (iv) providing a quantitative model of an RTS to evaluate its resiliency and/or optimising, recovering, or redesigning it (42.3 %) (e.g., Martello & Whittle, 2023; Yin et al., 2023). (v) Defining and designing a resilient culture routine, particularly in the planning stage of transportation systems (1.9 %) (e.g., Schulz et al., 2017). (vi) Delving into investment problems in implementing RTS plans (3.8 %) (e.g., Chen et al., 2018; Bwambale et al., 2023). (vii) Identifying and prioritising new technologies for RTS or ranking different ways of implementing intelligent transportation systems (9.6 %) (e.g., Deveci et al., 2023; Feng et al., 2023). This paper mainly elaborates on the second and third groups. Indirectly, the fourth class would be supported by the results of this research. Indeed, extracting and prioritising the resiliency factors for the international transportation system and depicting interactions between them must be included in the extant literature. These are fundamental inputs for future studies of the fourth category.

From another viewpoint, the type of event has not been specified in 40.4 % of recent works, albeit 40.3 % of scholars took a particular event under study (earthquake (15.4 %), flood (3.9 %), weather events (1.9 %), health crisis (7.7 %), health and financial dilemmas (1.9 %), transportation infrastructure failure (5.8 %), and accident (3.8 %)). Nevertheless, merely 19.2 % of them studied a wide collection of events (artificial disasters (3.9 %), natural disasters (2 %), or both (13.7 %)). Only 30 % contributed to the fourth (66.7 %) or the sixth (33.3 %) categories. As a result, the second research gap is evaluating the impacts of a wide collection of events on the resiliency factors of the international transportation system, which results in a set of strategies for future scholars and practitioners. Its shortcomings are even more noticeable as 37.3 % of reviewed articles ignored the geographical scope. Nonetheless, others bound their study to rural (2 %), urban (39.2 %), regional (19.6 %), and international (2 %) aspects. Therefore, the third identified gap is investigating resiliency factors for the international transportation system.

Moreover, 21.2 % of scholars did not distinguish the transportation mode they studied. Only one mode was addressed in 59.5 % of recent works (road (32.7 %), road-bridge (3.8 %), rail (7.7 %), maritime (11.5 %), and air (3.8 %)). Likewise, both road and rail modes were emphasised by 5.8 %. Nevertheless, three (air, maritime, and road: 1.9 %) and four modes (road, maritime, air, and rail: 11.5 %) were discussed in review papers. Nonetheless, maritime is a critical mode when scholars attempt to consider the international transportation system (Dui et al., 2021). Furthermore, China (33.3 %), the United States (19 %), and France (9.5 %) have been

Table 2
Resilient transportation system: A review of the relevant literature.

Scholars	Year	Main Contribution	Type of event (uncertainty)	Geographical scope	Transportation mode	Data Gathering	Data Analysis Qualitative	Quantitative	Data Type	Application (Studied case)
Azadeh et al.	2014	Exploring transportation resilience criteria of the supply chain and suggesting optimum policies to achieve them				D	SLR, CS	DEA, S	C, F	3-echelon supply chain
Holguín-Veras et al.	2014	Analysing the impacts of natural disasters on transportation resiliency	Earthquake, tsunamis	Regional		I, D		SA	C	Japan
Janić	2015	Modelling a Resilient Air Transportation System	LSDE		Air	D	CS	OM	C	16 airports on the north-east coast
Mattsson & Jenelius	2015	Clarifying future research agenda in terms of transportation resiliency	MD, ND	Urban	Air, maritime, road	D	SLR, CA		QL	
Reggiani et al.	2015	Reviewing recent research on transportation resiliency and vulnerability				D	SLR, CA		QL	
Adjetey-Bahun et al.	2016	Simulating a railway transportation system to quantify its resilience indicators		Urban	Rail	D	CS	S	C	Paris
Lyons & Davidson	2016	Providing a strategic guideline toward transportation resiliency		Urban	Road	D	CS, SP		QL	New Zealand's land transport program
Wang et al.	2016	Identifying significant integration of vulnerable linkage in transportation systems		Regional	Road	D	CS	OM	C	Tobin, Sioux Falls, etc. USA
Chen et al.	2017	Assessing transportation resiliency		Urban	Road, rail (freight)	D	CS	OM, S	C	Gothenburg Port, Sweden
Ferreira et al.	2017	Discussing transportation resiliency strategies				D	SLR, IA		QL	
Fonseca et al.	2017	"Providing spatial dissimilarity for environmental performance and resilient behaviour in energy and transportation systems"		urban		D	CS	OM	C	Industrial neighbourhood in Switzerland
Schulz et al.	2017	"Institutionalising resilience in intergovernmental transportation planning processes"	Flood	Urban	Road- bridge	I, Q, D		SA	C	Northeastern United States
Yang et al.	2017	Investigating freight transportation systems subject to the physical internet		Urban	Road, rail (freight)	D	CS	S	C	France
Azadeh et al.	2018	Evaluating the performance of transportation system resiliency		Urban	Rail	Q		DEA, SA	C	Tehran–Karaj railway, Iran
Chen et al.	2018	"Assessing the strategic investment of players in a port–hinterland container transportation network"	MD		Maritime	D		GT, SA	PS	Ningbo Zhoushan Port (NZP), China
Liu et al.	2018	Evaluating the impacts of supply chain resiliency on enterprise performance			Maritime	Q		SA, SM	C	Taiwanese liner shipping industry (253 companies)
Wan et al.	2018	Reviewing the extant literature in the context of transportation resiliency			All	D	SLR, CA		QL	
Ganin et al.	2019	Evaluating smart transportation resiliency	MD	Urban		D	CS	OM	S	Ten urban smart areas
Li et al.	2019	Assessing the post-catastrophe transportation system	Earthquake	Urban	Road (freight)	D	CS	OM	C, PS	
Markolf et al.	2019	Providing in-depth insight into transportation resiliency	Weather events		Road	D	SLR, IA		QL	
Twumasi-Boakye & Sobanjo	2019	Reviewing the extant literature in the context of transportation resiliency	MD, ND		Road	D	SLR, CA		QL	
Wang et al.	2019	Analysing water transportation resiliency	Accident	Urban	Maritime	D	IA, CS		QL	Chania Eastern Star
Zhang et al.	2019	Optimising network reconfiguration for developing transportation resiliency	ND			D	SLR	OM	C	
Zhou et al.	2019	Reviewing transportation resiliency literature	MD, ND		All	D	SLR, CA		QL	
Ahmed & Dey	2020	Extracting resilience indicators to model resilience transportation	MD, ND		All	D	SLR, CA		QL	
Gu et al.	2020	Evaluating transportation performance under disruptions		Urban	Road	D	CS, COA	OM	QL, C	Sioux-Falls

(continued on next page)

Table 2 (*continued*)

Scholars	Year	Main Contribution	Type of event (uncertainty)	Geographical scope	Transportation mode	Data Gathering	Data Analysis Qualitative	Quantitative	Data Type	Application (Studied case)
Sun et al.	2020	Reviewing recent research on transportation infrastructure resiliency under disruptions	MD, ND		All	D	SLR, CA		QL	
Zamanifar and Hartmann	2020	Reviewing the optimal planning model of disaster recovery transportation			Road	D	SLR, CA		QL	
Cimellaro et al.	2021	Assessing building and transportation resiliency impacted by calamities	Earthquakes	Urban	Road	D		OM	C	San Francisco Bay area
Dui et al.	2021	Optimising Maritime Transportation Resiliency	FTI	International	Maritime	D		OM	C	Sea routes of 23 cities
Gao & Wang	2021	Proposing a trackable resilience evaluation framework		Urban	Road (freight), rail (metro)	D		OM	C	Hangzhou, China
Notteboom et al.	2021	Comparing two kinds of crisis in the context of transportation resiliency	HC, FC		Maritime	D, Q	COA		QL	Shipping and port industries
Nipa Kermanshachi	2021	Extracting the indicators of assessing transportation resiliency			Road	D	SLR, CA		QL	
Pan et al.	2021	Categorising the extant studies related to transportation resiliency and clarifying future research agenda			All	D	SLR, CA		QL	
Tonn et al.	2021	Providing suggestions to improve transportation infrastructure resiliency	ND, MD			D, I	SLR, CA	SA	C, QL	U.S.A transportation
Twumasi-Boakye & Sobanjo	2021	Evaluating the transportation resiliency	FTI	Regional	Road	D		OM, WM	F, C	Escambia's Road transportation system
Wu et al.	2021	Assessing the resilience performance of the transportation system according to recovery priority	Earthquakes	Regional	Road	D		OM, S, SA	C	The traffic system of Centerville
Chen et al.	2022	Evaluating the resilience of a rail transit network		Urban	Rail (transit)	D		OM, S	C	Chengdu Subway in China
Du et al.	2022	Investigating the context of integrated urban transport resiliency	External shock	Urban	All	D	SLR, CA		QL	
Ghazy et al.	2022	Analysing the role of new technologies toward resilience infrastructure		Regional	Road	I, Q	DT	SA	QL, C	Malaysian transportation system
Pei et al.	2022	Assessing the resilience of interdependent transportation–healthcare system during an urgent situation	Earthquake	Urban	Road	D		OM	C	Interdependent transportation–healthcare system
Serdar et al.	2022	Providing resilience evaluation framework for transportation systems	ND, HC, intentional attacks	Urban		D	SLR, CA		QL	
Vishnu et al.	2022	Evaluating the resiliency and sustainability of transportation systems	Earthquake	Regional	Road	D		OM, SA	C	The road network in Memphis
Zhang et al.	2022	Optimising the infrastructure recovery scheduling after a disaster	Earthquake	Rural	Road-bridge	D		OM	C	The traffic system in a rural area of China

(*continued on next page*)

Table 2 (*continued*)

Scholars	Year	Main Contribution	Type of event (uncertainty)	Geographical scope	Transportation mode	Data Gathering	Data Analysis Qualitative	Data Analysis Quantitative	Data Type	Application (Studied case)
Bwambale et al.	2023	Evaluating customers interest in paying for extra services toward safety	HC	Regional	Road (public)	Q	SLR	RUT	C	Uganda and Bangladesh
Deveci et al.	2023	Ranking self-powered sensor-based cooperative intelligent transportation systems		Regional	Road	Q	SLR	MCDM	PS	
Feng et al.	2023	Discussing the role of Digital Twins and block chains in intelligent transportation systems influenced by travellers changing behaviour		Urban	Road	D	SLR	OM	QL	Road transportation industry (Xi'an Railway Station)
Gu & Liu	2023	Providing a future research agenda in the context of maritime transportation resiliency	HC		Maritime	D	SLR, CA		QL	
Martello & Whittle	2023	Discussing transportation systems resiliency impacted by a natural disaster (flood) as a result of climate change	Flood	Regional		D	SLR, CS, IA	OM	C, QL	Coastal cities
Wang et al.	2023	Evaluating diverse impacts of the COVID-19 pandemic on air traffic in different provinces	HC	Regional	Air	D	SLR	SA, OM	C	The aviation industry in China
Yin et al.	2023	Proposing a combinational model to evaluate urban transportation resiliency	Flood, Earthquake, Accident, FTI	Urban		D	SLR, CS	S, OM, SA	C	40 cities in China

Type of event (uncertainty). (i) MD: Man-made Disasters, (ii) ND: Natural Disasters, (iii) LSDE: Large-scale Disruptive Events, (iv) FTI: Failures of Transportation Infrastructure, (v) HC: Health crisis (Covid-19 outbreak), (vi) FC: Financial Crisis of 2008–2009.
Data gathering. (i) D: Documents and observations, (ii) I: Interview, (iii) Q: Questionnaire and survey.
Data analysis. (i) CS: Case Study, (ii) SLR: Systematic Literature Review, (iii) CA: Content Analysis, (iv) SP: Scenario Planning, (v) IA: Interpretive Analysis, (vi) COA: Comparative analysis, (vii) DT: Delphi Technique, (viii) OM: Optimisation Model, (ix) S: Simulation, (x) DEA: Data Envelopment Analysis, (xi) SA: Statistical Analysis, (xii) GT: Game Theory, (xiii) SM: Structural Modeling, (xiv) WM: Weighting Methods, (xv) RUT: Random Utility Theory.
Data type. (i) C: Crisp, (ii) QL: Qualitative, (iii) F: Fuzzy, (iv) PS: Stochastic/Probabilistic.

frequently studied. However, emerging economies such as Iran, Bangladesh, and Uganda have rarely been addressed. Moreover, port and shipping industries (23.1 %), aviation (15.4 %), railway electrification systems (15.5 %), and traffic systems (15.4 %) have often been emphasised. Nonetheless, sea routes, subways, healthcare systems, and container intermodal transportation systems have rarely been studied. This study focuses on Iran's maritime international transportation system to compensate for this shortage by considering sea routes, ports, containers, and the shipping industry. This case is essential when Iran is ranked fourth for proven crude oil reserves (The World Bank, 2022), which has crucial impacts on the global transportation system as a product or a fuel.

From a methodological lens, data collection has been performed with three approaches and a combination of them in some papers (i.e., documents and observations (52 %); documents, observation, questionnaire, and survey (32 %); questionnaire and survey (8 %); interview, documents, and observations (4 %); interview, documents, observation, questionnaire, and survey (2 %); interview, questionnaire, and survey (2 %)). Hence, documents, questionnaires and surveys favour this area. Indeed, a questionnaire is a time- and cost-efficient tool to collect extra data associated with experts' views, which have been used in this research.

Moreover, 37.3 % of reviewed research analysed the compiled data with both qualitative and quantitative methods (i.e., case study and optimisation model (26.3 %); case study and simulation (10.5 %); SLR and optimisation (10.5 %); SLR and multi-criteria decision making (MCDM) (5.3 %); Delphi technique and statistical analysis (5.3 %)). Plus, 35.3 % proceeded with qualitative methods (e.g., SLR and content analysis (72.2 %); SLR and interpretive analysis (11.1 %)). The rest of the scholars (27.5 %) employed quantitative approaches (e.g., optimisation model (35.7 %), statistical analysis (14.3 %), optimisation and weighting (7.1 %)). Ergo, mixed methods are more acknowledged in this domain to obtain more reliable outcomes, which has been considered in this research. Nonetheless, MCDM has rarely been combined with qualitative methods. Thus, employing an integrated framework of SLR, SFD, and spherical fuzzy DEMATEL-ANP is a novelty in this context. On the other hand, although 60.8 % of scholars dealt with quantitative data, they mainly applied crisp numbers (81.3 %). However, fuzzy (9.3 %), stochastic (6.2 %), and probabilistic (3.1 %) values have recently been employed to consider uncertainties of the environment, hesitation, and intuition of experts views. As a result, designing and employing a new version of uncertainty approaches, like a spherical fuzzy set, is necessary and innovative in this field.

3. Methodology

This research employed a mixed-method approach, integrating both qualitative and quantitative analyses. The qualitative phase utilised an exploratory approach (Fetters et al., 2013), initiating a comprehensive SLR to identify and extract the criteria and sub-criteria of resiliency factors for a resilient transportation system. Detailed descriptions of the literature review findings are presented in Section 4. Subsequently, the outcomes from the qualitative phase served as the foundation for the quantitative analysis. Notably, all quantitative analyses use spherical fuzzy sets to account for uncertainty in real dynamic environments and to model expert opinions with enhanced precision and realism (Kutlu Gündoğdu & Kahraman, 2019).

Spherical fuzzy sets represent an extension of Zadeh's fuzzy sets (Zadeh et al., 1996) and Atanassov's intuitionistic fuzzy sets (Atanassov, 1994), encompassing a neutrality degree in addition to membership and non-membership degrees (Ashraf et al., 2019). This extension pictures fuzzy sets (Cuong & Kreinovich, 2013) and enables experts to express their opinions more flexibly. In addition, experts' arguments about the availability, unavailability, and neutrality of the factors are not restricted to limiting the summation to 1. Instead, they can sum the squared degrees to 1, akin to Pythagorean fuzzy sets, allowing them to convey ambiguity without constraints (Peng & Selvachandran, 2019). The results from the SLR serve as the input for the SF-Delphi technique, a structured and iterative group communication process involving expert panels to seek consensus on critical resiliency factors (Abbasi Kamardi et al., 2022).

Following the Delphi technique, experts further evaluated the outcomes to determine the relationships between each criterion and other criteria. Hence, the most available factors obtained through Delphi were analysed using the SF-DANP method, prioritising the factors based on their levels of influence (Kamardi & Sarmadi, 2023). Combining qualitative and quantitative methods and applying spherical fuzzy sets ensured a robust and nuanced exploration of resiliency factors critical for enhancing transportation system resilience in dynamic and uncertain environments (Jafari-Sadeghi et al., 2021; Amoozad Mahdiraji et al., 2023). The research framework is illustrated in Fig. 2, and a detailed description of each phase is elaborated after.

3.1. Data collection

This research used a mixed-method approach to benefit from primary and secondary data. The secondary data were applied to extract the list of critical factors for the resilience of transportation systems through an SLR. Furthermore, primary data were employed to screen the list of factors, measure the importance of the selected factors, classify the selected factors, and present a conceptual framework of the selected factors' impacts on international transportation resiliency. As explained in Section 2, extracting the initial list of critical factors of a resilient transportation system was based on investigating the available literature using an SLR framework. This research employed two primary data-gathering stages to investigate the extracted factors: (i) spherical fuzzy analysis and (ii) spherical fuzzy DEMATEL-ANP (SFDANP).

For each stage, a spherical fuzzy questionnaire was designed and employed. Three panels of experts completed these questionnaires. Each panel of experts included (i) one academic member to facilitate the data gathering, briefly introducing the research, and supporting other members on how to complete the questionnaires; (ii) two industry-level experts from Iranian transportation companies; and (iii) two official level experts from the Islamic Republic of Iran Shipping Line Group (IRISL), or Ministry of Industry, Mine and Trade (MIMT), or Ministry of Petroleum (MoP). Hence, 15 experts participated in this research to complete each questionnaire. For industry-level and official-level experts, the minimum qualifications included (i) at least 35 years old; (ii) at least five years experience in international transportation companies, IRISL, MIMT, or MoP, and its subsidiaries located in the Persian Gulf; (iii) at least a

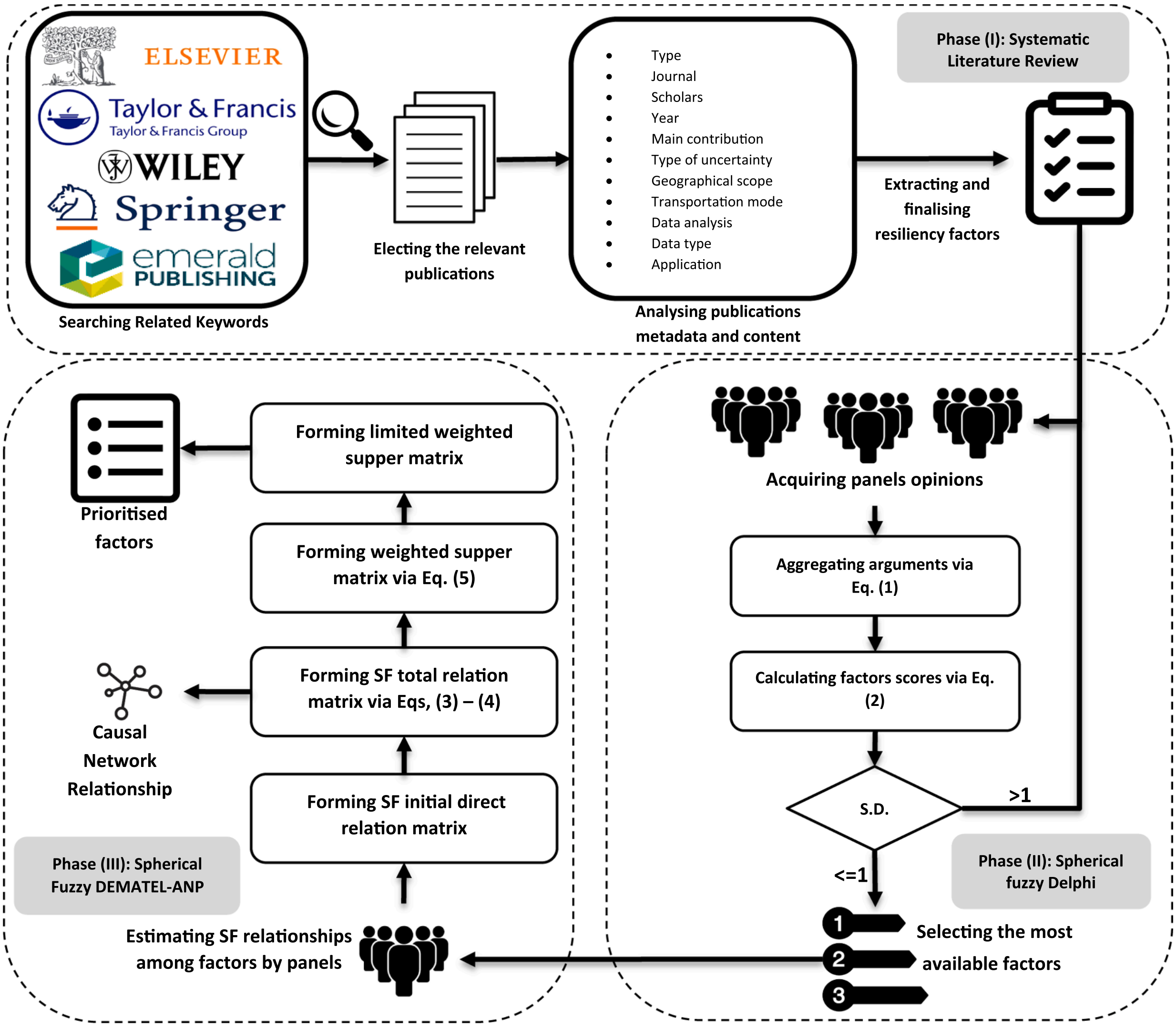

Fig. 2. Research Framework.

bachelor's degree in management science, or transportation/civil/industrial engineering; and (iv) participated in at least one workshop on resilient transportation. For the academic member of each panel, the minimum qualifications included (i) a relevant PhD in transportation, resiliency, or supply chain; (ii) at least 40 years old; and (iii) having published at least five reputable articles in the relevant area in the last three years.

For each questionnaire (i.e., SFD and SFDEMATEL), a two-hour briefing and discussion session was managed by the academic member of each panel to explain the research objectives, introduce the questionnaire, and explain how the initial list was extracted. Then, after two weeks (for each expert to complete the questionnaire individually), the second meeting was set, and the panel members finalised each questionnaire by sharing their opinions, discussing, and debating (minimum of two hours). As a result, one questionnaire was finalised by each panel in each stage and was used for further investigation in SFD and SFDEMATEL. Approximately 12 two-hour meetings with fifteen participants were managed during the primary data-gathering stage.

3.2. Phase (I): Systematic literature review

Conducting a thorough examination of academic literature within specific communities is crucial for assessing research patterns and establishing a structured framework. This process enables researchers to advance understanding within their field by critically assessing existing knowledge. As research expands, SLR has emerged as a trusted method for informing decision-making and guiding implementation strategies for various stakeholders (Tranfield et al., 2003). Hence, in this qualitative investigation phase, SLR was employed to meticulously and openly analyse the existing literature concerning international resilient transportation systems in uncertain conditions. As such, manual coding was utilised to assess articles and identify key resilient factors pertinent to international transportation systems facing unprecedented challenges. To this end, employing an appropriate protocol is imperative to avoid confusion. Therefore, we adopted SPAR-4-SLR, proposed by Paul et al. (2021). The SPAR-4-SLR protocol was chosen over other protocols due to its ability to address limitations found in alternative approaches, such as a lack of comprehensiveness and guidance for researchers (Paul et al., 2021). This procedure encompasses three primary stages: **(i)** assembling, **(ii)** arranging, and **(iii)** assessing scientific literature. Additionally, it includes six sub-stages: identification, acquisition, organisation, refinement, evaluation, and reporting, as elaborated in Fig. 3.

Stage 1. Assembling. Initially, the identification process was performed by defining the scope of research, outlining research inputs, and specifying the type and quality of sources. Secondly, through the **acquisition** sub-stage, search methods and materials, search timeframe, and keywords were determined. Overall, the resiliency factors in international transportation systems under uncertainty were examined. As such, English reviews, research articles, and chapters listed in Scopus and Web of Science were considered, particularly those belonging to five valid and popular databases: Elsevier, Springer, Taylor & Francis, Wiley, and Emerald. Besides, the Australian Business Deans Council (ABDC) served as a source of quality. Next, keywords were searched between 2014 and 2023 involving ((*"Resilience factors of" OR "Resilience"* OR *"Resilience in"* OR *"Resilience of"*) AND (*"Transportation systems"* OR *"Transportation networks"* OR *"International transportation systems"* OR *"International transportation systems"*)). As a result, 976 works were initially found.

Stage 2. Arranging. In this step, both **organisation** and **refinement** were adopted. Filters provided by Scopus and Web of Science were utilised. Firstly, 49 duplicated items were removed. Subsequently, the criteria, including title, research scope, keywords, document type, source quality, and language, were applied to 927 research. The similar keyword filters employed in the first stage led to the exclusion of 358 works. Only journal articles and book chapters were retained in the refinement stage, while 88 conference

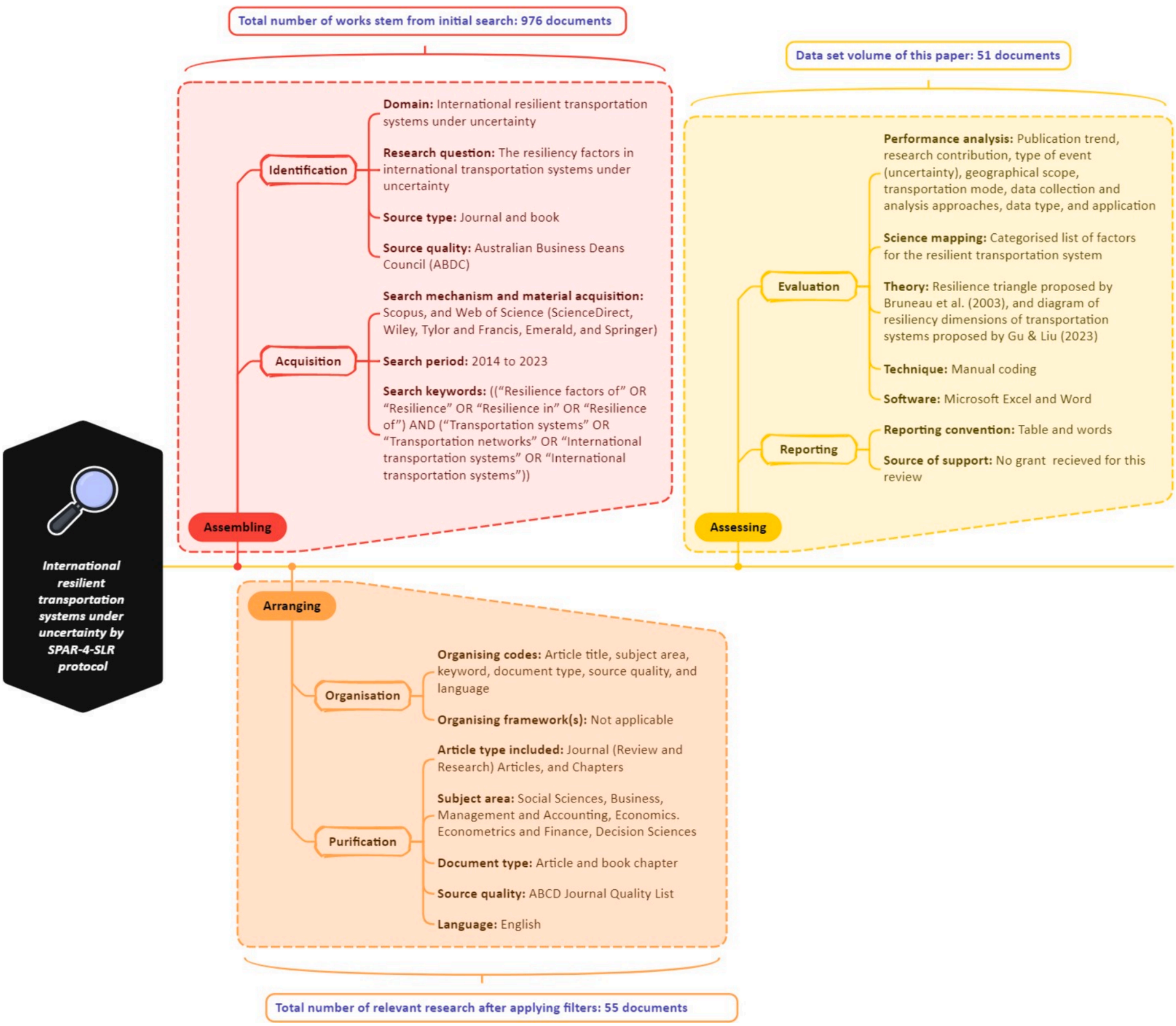

Fig. 3. Literature Review framework of international resilient transportation systems in uncertain conditions based on SPAR-4-SLR protocol.

articles and 12 special issues were discarded. Among 469 of the rest of the research, those focusing on the resilient factors in international transportation systems under uncertainties with subjects of social science, business, management, accounting, economics, econometrics and finance, and decision science were selected (100 research). Next, a language filter was applied, retaining only English articles and journals in ABDC. This process resulted in 55 articles passing the second stage, which were evaluated and analysed in the last phase.

Stage 3. Assessing. The final step in the SPAR-4-SLR protocol involves **evaluation** and **reporting**. Firstly, a depth scan, viz., fully reading 55 relevant studies' titles and abstracts, excluded four papers not provided with our research inputs. Hence, manual coding was adopted to assess the pool of extracted articles, totalling 51. Microsoft Excel and Word software were employed to report the information, with findings and analyses presented in Fig. 4 and Tables 2 and 3. More precisely, this paper dataset was evaluated using different data marts, such as publication trend, research contribution, type of studied events, geographical scope, transportation mode, data collation and analysis approaches, data type, and application. Subsequently, two paramount theories were applied to categorise the extracted resiliency factors, including the Resilience triangle proposed by Bruneau et al. (2003) and the diagram of resiliency dimensions of transportation systems proposed by Gu & Liu (2023).

Eventually, we took into account the data sources from prior research that employed SLR in analysing resilient transportation systems (e.g., Azadeh et al., 2014; Mattsson & Jenelius, 2015; Reggiani et al., 2015; Wan et al., 2018; Twumasi-Boakye & Sobanjo, 2019; Deveci et al., 2023; Gu & Liu, 2023, etc.), ensuring comprehensive coverage and confirming the accuracy of both the source list and the extracted list of resilient factors. As a result, we ensured that no significant research findings were overlooked and validated the inclusion of various resilient factors. Moreover, our study initially unveiled new categories, such as cognition, safety and security management, and functionality, which were neglected by previous investigations.

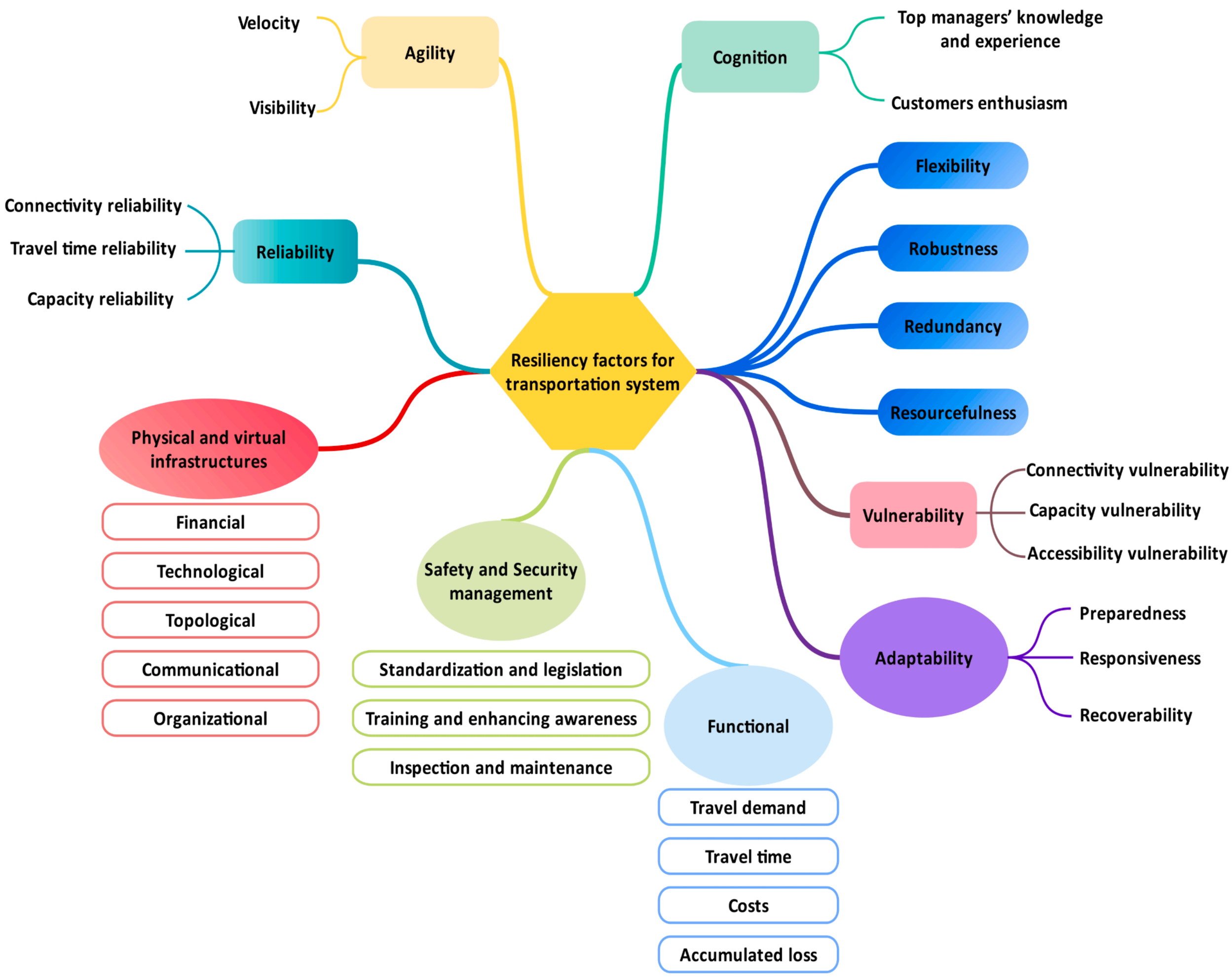

Fig. 4. Resiliency factors for the resilient transportation system, extracted by SLR.

Table 3
List of resiliency factors for the resilient transportation system.

Factor	Sub-factor	Definition	Reference
Flexibility		The system's potency to cope with, resolve, or even benefit from perturbations, particularly by resource reconfiguration. Regarding transportation systems, "flexibility can be used to describe the capacity of a system to handle and absorb changes and to emphasise the ''changes' on the demand side". It means the capacity to adapt to market changes and the allocation of resources. It is essential for the post-disruption phase. In contrast to robustness, flexibility persists to withstand or sustain changes by disturbance instead of adapting to them.	(Azadeh et al., 2014; Chen et al., 2017; Liu et al., 2018; Wan et al., 2018; Markolf et al., 2019; Twumasi-Boakye & Sobanjo, 2021; Pan et al., 2021; Serdar et al., 2022; Gu & Liu, 2023; Martello & Whittle, 2023)
Robustness		Reflects the transportation system's resistance to disruptions. Hence, it refers to this system's strength in enduring, absorbing, or adapting to disturbances while continuing its operations. Robustness is a crucial resilience factor exactly during a disruption.	(Reggiani et al., 2015; Adjetey-Bahun et al., 2016; Wang et al., 2016; Liu et al., 2018; Wan et al., 2018; Markolf et al., 2019; Twumasi-Boakye & Sobanjo, 2019; Gu et al., 2020; Gao & Wang, 2021; Pan et al., 2021; Twumasi-Boakye & Sobanjo, 2021; Zhang et al., 2022; Serdar et al., 2022; Martello & Whittle, 2023; Gu & Liu, 2023)
Adaptability	Preparedness	Reflects the transportation system's ability in the readiness phase (before an unexpected event) when it tries to prepare for an unexpected event (emergency preparedness and response preparedness) by employing prominent proceedings, e.g., anticipation, monitoring, and learning.	(Chen et al., 2018; Wan et al., 2018; Wang et al., 2019; Nipa & Kermanshachi, 2021; Gu & Liu, 2023; Martello & Whittle, 2023)
	Responsiveness	Indicates the transportation system's capability in the response phase when it attempts to respond to the perturbation by employing prominent actions.	(Wan et al., 2018; Gu & Liu, 2023)
	Recoverability	Presents the potency of the transportation system in the recovery phase; when it intends to timely amend the disrupted system after the turbulence by employing prominent measures, it is noteworthy that the considered system may have to build a completely new system in this phase. It is acknowledged as a critical indigent of safe and efficient shipping networks.	(Wan et al., 2018; Pan et al., 2021; Gu & Liu, 2023; Martello & Whittle, 2023)
Agility	Velocity	Refers to the rapidity of the transportation system to be recovered after an unexpected event that greatly hits the demand–supply cycle. It refers to recovering functions as soon as possible in a timelier manner.	(Azadeh et al., 2014; Liu et al., 2018; Markolf et al., 2019)
	Visibility	Reflects transparent traceability of inventory management, demand–supply cycle, scheduling, etc. Additionally, it indicates visibility and trust in communication and information sharing.	
Redundancy		Reflects the transportation systems' strength in operating while some ingredients are missing, owing to extra valency of talents, materials, etc., at potential pinch points. For instance, "In this case, redundancy usually appears as the existence of optional routes between origins and destinations." the capacity of the maritime system to take some contingency measures to keep its overall performance exactly during a disruption. E.g., duplicating the prominent operations of the system and applying backup functional modules like more alternative routes.	(Azadeh et al., 2014; Adjetey-Bahun et al., 2016; Azadeh et al., 2018; Liu et al., 2018; Wan et al., 2018; Twumasi-Boakye & Sobanjo, 2019; Zhou et al., 2019; Nipa & Kermanshachi, 2021; Twumasi-Boakye & Sobanjo, 2021; Wu et al., 2021; Zhang et al., 2022; Feng et al., 2023; Gu & Liu, 2023)
Resourcefulness		Refers to the transportation system's ability to mobilise internal and external resources, such as human capital, materials, budget, etc., to help the system recover actions in facing disruptions during a recovery phase. Resource accessibility and prioritising are two prominent elements in this regard.	(Adjetey-Bahun et al., 2016; Twumasi-Boakye & Sobanjo, 2019; Pan et al., 2021; Wan et al., 2018; Zhang et al., 2022)
Reliability	Connectivity reliability	Indicates "the probability of the nodes in a transportation network remaining connected".	(Mattsson & Jenelius, 2015; Reggiani et al., 2015; Chen et al., 2017; Azadeh et al., 2018; Ahmed & Dey, 2020; Gu et al., 2020; Dui et al., 2021; Gao & Wang, 2021; Pan et al., 2021; Serdar et al., 2022; Gu & Liu, 2023)
	Travel time reliability	Presents "the probability of reaching a destination within a given travel time".	
	Capacity reliability	Denotes "the probability of whether a network can satisfy a specified demand under degraded network condition".	

(continued on next page)

Table 3 (*continued*)

Factor	Sub-factor	Definition	Reference
Vulnerability	Connectivity vulnerability	It is a negative feature that calculates connectivity reduction based on specified topology indicators	(Mattsson & Jenelius, 2015; Wang et al., 2016; Chen et al., 2018; Wan et al., 2018; Markolf et al., 2019; Ganin et al., 2019; Gu et al., 2020; Ahmed & Dey, 2020; Cimellaro et al., 2021; Wu et al., 2021; Dui et al., 2021; Gao & Wang, 2021; Pan et al., 2021; Pei et al., 2022; Serdar et al., 2022; Gu & Liu, 2023)
	Capacity vulnerability	It reflects capacity pinch, which leads to grid disruption with insufficient capacity	
	Accessibility vulnerability	It refers to weakness in accomplishing apparent chances, such as travel costs stemming from traffic assignments to provide network efficiency and effectiveness	
Physical and virtual infrastructures	Financial	Reflects liquidity volume and fund accessibility in promoting transportation system performance in the case of unexpected events. In this respect, two subjects of type and case of investment form critical decisions. For instance, investment in preventive processes is one of the best choices.	(Reggiani et al., 2015; Schulz et al., 2017; Liu et al., 2018)
	Technological	Reflects creating innovation and utilising advanced technologies, e.g., shared vehicles, drones, robotics, Internet of Things, and blockchain, to enhance the transportation system performance in case of perturbations. For instance, “data sharing between vehicles and infrastructure” is an innovative action to do so.	(Holguín-Veras et al., 2014; Adjetey-Bahun et al., 2016; Ganin et al., 2019; Ghazy et al., 2022; Pei et al., 2022; Serdar et al., 2022; Deveci et al., 2023; Feng et al., 2023)
	Topological	Refers to transportation network connectivity, viz. accessibility, which emphasises the arrangement of nodes and links, particularly their locations and the nature of their connections. Focusing on two types of international and local connectivity is essential.	(Reggiani et al., 2015; Gao & Wang, 2021; Wu et al., 2021; Deveci et al., 2023; Yin et al., 2023)
	Communicational	In case of a perturbation, real-time data, knowledge, and information sharing are critical elements of a resilient transportation system. To this end, a disaster database will help perform prevention actions. Besides, integration and collaboration with external partners and relevant authorities is another communicational infrastructure to deal with it.	(Holguín-Veras et al., 2014; Azadeh et al., 2014; Deveci et al., 2023)
	Organisational	Some characteristics such as teamwork, promoting organisational culture, self-organisation, re-engineering, etc., can be useful for a transportation system to cope with an unexpected event.	(Azadeh et al., 2018; Chen et al., 2018; Liu et al., 2018; Nipa & Kermanshachi, 2021)
Cognition	Top managers knowledge and experience	Reflects the top managers’ knowledge and experience in previous crises when managing a transportation system.	(Schulz et al., 2017; Liu et al., 2018; Markolf et al., 2019; Nipa & Kermanshachi, 2021; Serdar et al., 2022 Gu & Liu, 2023)
	Customers enthusiasm	Reflects the degree of importance of safety issues from the customers’ mindset, which makes them enthusiastic to pay costs for extra safety and sanitary options. This also impacts their demand pattern.	(Bwambale et al., 2023)
Safety and Security management	Standardisation and Legislation	Refers to the vital standards and laws crucial for managing proactive safety and security. For instance, particular standards and rules for reforming the workforce, performing formal processes, safety supervision guidance, etc.	(Adjetey-Bahun et al., 2016; Chen et al., 2017; Chen et al., 2018; Twumasi-Boakye & Sobanjo, 2019; Zhou et al., 2019; Bwambale et al., 2023; Deveci et al., 2023)
	Training and enhancing awareness	Reflects the necessity of holding appropriate training courses for human capital related to safety and security issues, facing disasters, etc. This leads to human resource awareness and promoting safety, disasters, etc.	(Chen et al., 2018; Liu et al., 2018; Ghazy et al., 2022)
	inspection and maintenance	Refers to carrying out ordered and precise checks on the daily operation of human resources and devices. Which stem from a coherent plan of maintenance and repair.	(Dui et al., 2021; Tonn et al., 2021; Ghazy et al., 2022; Deveci et al., 2023)
Functional	Travel demand	Refers to the flow of passengers or freight volume that should be transferred.	(Li et al., 2019; Ahmed & Dey, 2020; Wu et al., 2021)
	Travel time	It is a scale of the time necessary to travel from the current place to the destination.	(Zhou et al., 2019; Ahmed & Dey, 2020; Gao & Wang, 2021; Twumasi-Boakye & Sobanjo, 2021; Pei et al., 2022; Serdar et al., 2022; Yin et al., 2023; Zhang et al., 2022)
	Costs	Reflects different costs (e.g., operational costs, expected failure costs, travel costs) that the transportation system must bear.	(Chen et al., 2017; Wan et al., 2018; Zhou et al., 2019; Gao & Wang, 2021; Nipa & Kermanshachi, 2021; Tonn et al., 2021; Twumasi-Boakye & Sobanjo, 2021; Zhang et al., 2022; Serdar et al., 2022; Bwambale et al., 2023)
	accumulated loss	Refers to the annual losses left undistributed, which have not been debited to the partner’s capital account.	(Wang et al., 2023)

3.3. Phase (II): Spherical fuzzy Delphi

The spherical fuzzy theory considers three membership degrees of positive P_A, neutral I_A, and negative N_A of (r) in (R), under two conditions of $\{P_A, I_A, N_A : R \rightarrow [0,1]\}$ and $\{0 \le P_A^2 + I_A^2 + N_A^2 \le 1\}$ (Kutlu Gündoğdu & Kahraman, 2019). R represents a universal set, and its spherical fuzzy set is $A = \{\langle r, P_A(r), r, I_A(r), r, N_A(r) | r \in R\rangle\}$. Accordingly, five steps of the SFD algorithm are expressed below.

Step 1. Identifying Factors. This paper extracted a categorised list of resiliency factors for the international resilient transportation system through SLR. The results are illustrated in Table 2.

Step 2. Acquiring Spherical Fuzzy Arguments. In this step, a questionnaire invited three expert panels $P_i(i = 1,2,3)$, each consisting of five members, to estimate the availability, neutrality, and unavailability of selected factors. To this end, three respective {-Available, –Neutral, and –Unavailable} five-point linguistic scales {Absolutely-, Very-, Pretty-, Nearly-, and Not-} were employed. Each corresponds to a spherical fuzzy number (SFN) $\{0.8, 0.6, 0.4, 0.2, 0\}$, respectively.

Step 3. Aggregating Spherical Fuzzy Arguments. $SFS_j = \{e_{P_i}\} \quad (i = 1,2,3 \quad and \quad j = 1,\cdots,n)$ was accomplished for each factor by transforming linguistic terms into the equivalent SFNs. For each spherical fuzzy set (SFS), e_{P_i} was then aggregated by the spherical fuzzy hybrid weighted averaging operator (SFNHOWAA) as follows.

$$SFNHOWAA_\omega(e_{P_1}, e_{P_2}, e_{P_3}) = \prod_{P_i=1}^{3} \tau_{P_i \mathring{e}_\eta(P_i)} \tag{1}$$

In Equation (1), $\omega_i = (\omega_1, \omega_2, \omega_3)$ is the weighting vector of spherical fuzzy arguments e_{P_i}, such that $\sum_{i=1}^{n} \omega_i = 1$, and $n = 3$ represent the balancing coefficient (Kutlu Gündoğdu & Kahraman, 2019).

Step 4. Computing Score Function and Inquiring Consensus. The score function of each aggregated SFN $Sc(e_j)$ was computed as follows (Kutlu Gündoğdu & Kahraman, 2019).

$$Sc(e_j) = \frac{1}{3}\left(2 + P_{e_j} - I_{e_j} - N_{e_j}\right), (j = 1,2,\cdots,n) \tag{2}$$

Next, the consensus of the views was tested. The suggested SFD algorithm will stop if the standard deviation of Sc_j is less than 1. Otherwise, the process should be repeated from step 2.

Step 5. Selecting the ideal factors. The most available factors in Table 2 were selected by setting a threshold value of $\alpha = 0.7$. If $Sc_j \ge \alpha$, then the factor is recognised as available; otherwise, it is removed from the list.

3.4. Phase (III): Spherical fuzzy DEMATEL and ANP (SFDANP)

By integrating SFS, DEMATEL and ANP methods (Razavi Hajiagha et al., 2022), SFDANP is developed in this research through the following steps.

Step 1. Estimating the Spherical Fuzzy Relationships Amongst Factors. Three panels were invited to estimate the relationships among the ideal factors selected by SFD. A questionnaire was distributed in which three respective degrees {- Influenced, –Neutral, and – Uninfluenced} and five-point linguistic scales {Extremely-, Highly-, Nearly-, Meagerly-, Not-} were considered.

Step 2. Forming Spherical Fuzzy Initial Direct Relation Matrix (SFIDRM). The acquired linguistic terms were transformed to an equivalent SFN, as applied in step 2 of SFD. Later, the SFSs for every two factors were achieved, and SFNHOWAA then aggregated their SFNs. Analogues to step 4 of SFD, the score function of each aggregated SFN was measured. Eventually, the SFIDRM was formed for selected factors, $SFIDRM_C = \left[x_{ij}^C\right]_{m\times m}$, such that $(i = j = 1,\cdots,m)$.

Step 3. Forming Spherical Fuzzy Total Relation Matrix (SFTRM). Firstly, the SFIDRM was normalised as follows.

$$SFIDRM_C{}^N = min\left\{\frac{1}{max\left\{\sum_{j=1}^{m} x_{ij}^C\right\}}, \frac{1}{max\left\{\sum_{i=1}^{m} x_{ij}^C\right\}}\right\} \times \left[x_{ij}^C\right]_{m\times m} \tag{3}$$

Afterwards, the SFTRM was measured as follows, where I presents an $m \times m$ identity matrix.

$$SFTRM_C = SFIDRM_C{}^N \times \left(I - SFIDRM_C{}^N\right)^{-1} = \left[z_{ij}^C\right]_{m\times m} \tag{4}$$

Step 4. Mapping Causal Network Relationship Framework. The sum of the row R_i and column D_i of $SFTRM_C$, along with $(R_i + D_i)$ and $(R_i - D_i)$, were calculated for factors. If $(R_i - D_i)$ is positive (or negative), then the factor is a cause (or effect). Moreover, a binary relation matrix depicted the causal network relationship framework for factors. In so doing, a threshold value was assumed as the average of SFTRM's elements. If an SFTRM's element is equal to or higher (or lower) than that threshold value, that element was substituted with 1 (or zero). Hence, for each value of 1, a single-headed arrow was recorded from i to j.

Step 5. Forming a Weighted Supper Matrix (WSM). Initially, the normalised matrix N^C was formed as below.

$$N^C = \begin{bmatrix} \frac{z_{11}^C}{d_1} & \cdots & \frac{z_{1n}^C}{d_1} \\ \vdots & \ddots & \vdots \\ \frac{z_{n1}^C}{d_n} & \cdots & \frac{z_{nn}^C}{d_n} \end{bmatrix} \quad where \quad d_k = \sum_{j=1}^{n} z_{ij}^C. \tag{5}$$

Later, the $\text{WSM}_T = \left[w_{ij}^C\right]_{n\times n}$ was acquired by transposing N^C.

Step 6. Forming Limited Weighted Supper Matrix (LWSM). The *WSM* was raised to the extreme power until the *LWSM* contained constant convergence values. Hence, the factor weight was considered as this unique value of each row of *LWSM*.

4. Result

According to Table 2, 12 factors and 22 sub-factors were responsible for a resilient transportation system after implementing the SLR. Table 3 provides a brief explanation of each factor.

Delving into previous studies, presented in Tables 2 and 3, a list of resiliency factors for the resilient transportation system is illustrated in Fig. 4.

As stated, few recent papers have focused on the resiliency factors of maritime transportation systems, as illustrated in Table 2. Moreover, the international level was also not frequently emphasised. To compensate for these drawbacks, we employed experts' opinions via SF-Delphi to ensure that the extracted factors are reliable for the resiliency of international maritime transportation systems, particularly for emerging economies like Iran. Subsequently, three distinct panels of experts were meticulously assembled, and each was tasked with evaluating the availability, unavailability, and neutrality of the factors by utilising the SF-Delphi approach, ensuring a comprehensive evaluation process. Engaging these expert panels captured diverse perspectives, contributing to a robust analysis of the factors at hand. The SFNHOWAA operator mentioned in Eq.1 was employed to distil these multifaceted opinions into a cohesive framework. The results are presented in Fig. 5, underscoring the degree of availability, unavailability, and neutrality of the factors. Additionally, experts were asked to add other important factors that do not exist in the initial list of extracted factors. Nonetheless, they confirmed this list and did not add any more factors. Accordingly, the finalised factors are reliable for the considered case based on the extant literature and experts' views. The SFD questionnaire is presented in Appendix 2.

After consolidating the insights of the expert panels, the next step involved calculating the spherical fuzzy score for each factor using Eq.2, with the outcomes visualised in Fig. 6. Notably, the bold red line in the visualisation serves as a critical threshold, distinguishing factors primed for further analysis. Factors exceeding this threshold signify a notable level of availability, thereby warranting deeper investigation. This threshold was specifically set at 2/3 of the availability score.

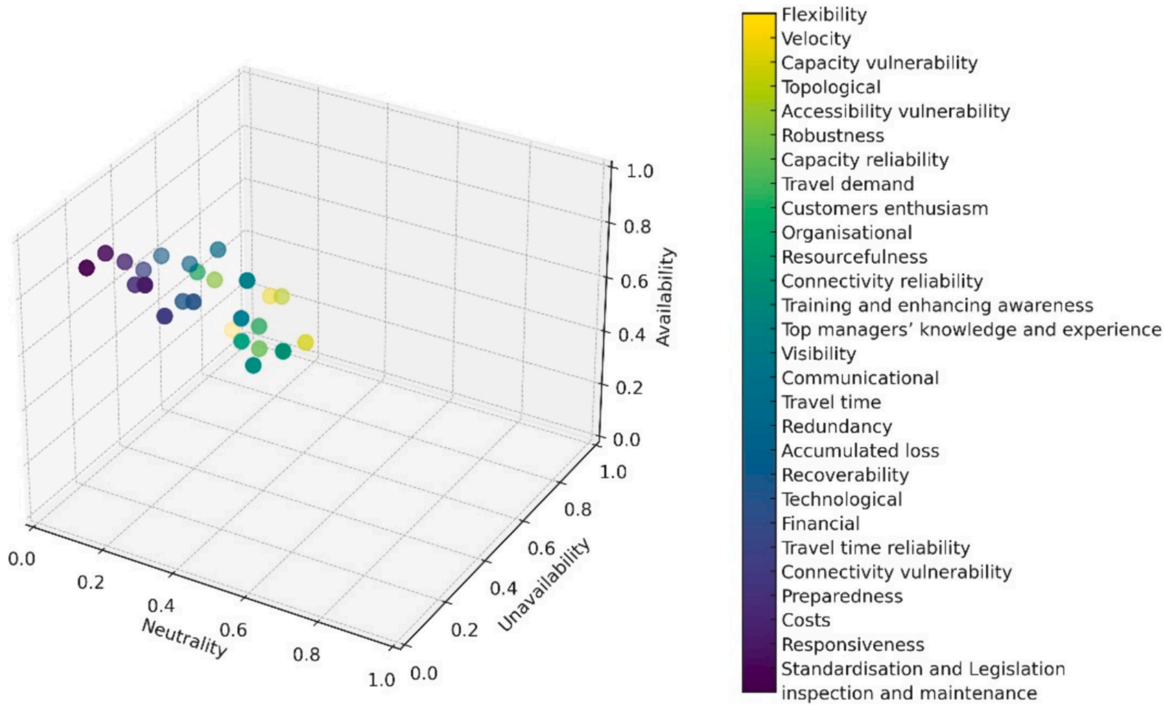

Fig. 5. SFDelphi experts' integrated opinions.

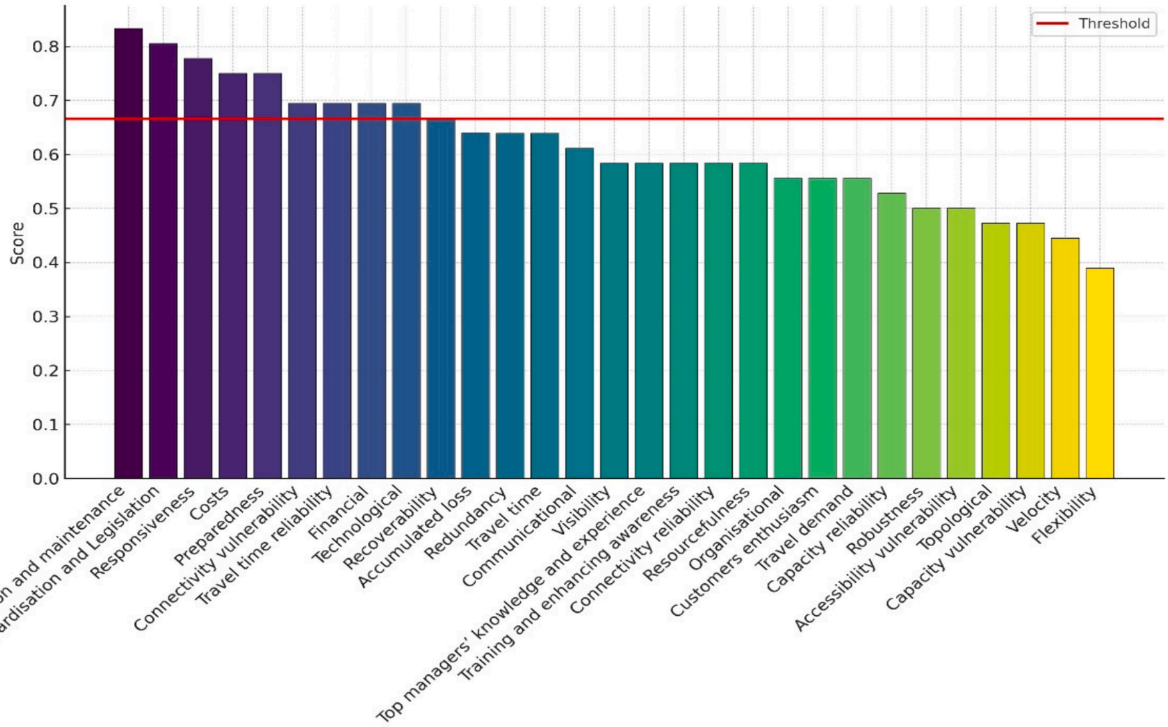

Fig. 6. Spherical fuzzy Delphi results.

Among the various approaches to classical fuzzy extensions, intuitionistic fuzzy sets incorporate non-membership alongside membership, considering that the sum of these two degrees should be less than or equal to 1 (Atanassov, 2012). This has led to two main streams of extensions within intuitionistic fuzzy sets. In one stream, a neutrality degree is introduced in addition to membership and non-membership, forming neutrosophic fuzzy sets, with the restriction that the sum of all three degrees should be less than or equal to 1 (Das et al., 2020). In another stream, limitations on these conditions are relaxed. Pythagorean fuzzy sets employ the condition that the sum of squares of membership and non-membership should be less than or equal to 1 (Peng and Yang, 2015), and Fermatean fuzzy sets use the condition that the cubes of the squares of membership and non-membership should be less than or equal to 1 (Senapati and Yager, 2020). In the proposed spherical method, we combined these two streams by incorporating a neutrality degree and addressing the limitation, specifying that the sum of the squares of all three degrees should be less than or equal to 1.

In other words, in our endeavour to model uncertainty comprehensively, we confronted the challenge of not constraining experts' opinions within the traditional bounds of fuzzy set extensions, such as intuitionistic and neutrosophic sets. The decision was rooted in our commitment to allowing experts to express their views without limiting the sum of their options' availability and unavailability to equal or be under 1. This approach facilitated a nuanced uncertainty translation into our model, ensuring a more accurate representation. Notably, experts incorporated the dimension of neutrality alongside availability and unavailability, fostering a deeper understanding of their perspectives and encouraging a greater willingness to share authentic opinions with fewer constraints. While we were unable to explore intuitionistic and neutrosophic score functions due to the specified condition mentioned below, we conducted a thorough examination using an alternative spherical fuzzy set score function, Pythagorean and Fermatean fuzzy sets, with the exclusion of neutrality. Hence, these methods were selected for three reasons: (i) We opted to employ and compare these novel fuzzy extensions instead of classical ones, providing a more contemporary and nuanced perspective. (ii) These methods enable the modelling of both availability and unavailability as expressed by experts, as they do not impose restrictions on their sums to be less than or equal to 1, allowing for a more flexible and realistic representation of expert assessments. The correlation of the proposed method in the current research is assessed against alternative spherical fuzzy (Kutlu Gündoğdu and Kahraman, 2019), PF (Zhou and Chen, 2019), and FF (Sahoo, 2021) methods using the Pearson correlation coefficient. The results, outlined in Fig. 7, revealed a strong correlation between our scores and those obtained from other methodologies. In cases where variations surfaced, validation procedures were meticulously conducted through expert consultation. The experts emphasised that our current score function more accurately captured their opinions, a viewpoint grounded in the diminished limitations elucidated earlier in the proposed method.

As depicted in Fig. 7 the score function exhibits a strong correlation with other possible approaches, particularly showcasing correlation coefficients of 0.89 with the Pythagorean fuzzy (PF2) score function, 0.88 with the Fermatean fuzzy (FF3) score function, and 0.88 with the alternative spherical fuzzy (SF4) score function. Since all subsequent computations rely on the score function, these high correlation values instil confidence in the validity of the model. The robust agreement between the scores generated by different methodologies reinforces the reliability and consistency of the proposed approach. The details of the FF, SF and PF score functions are

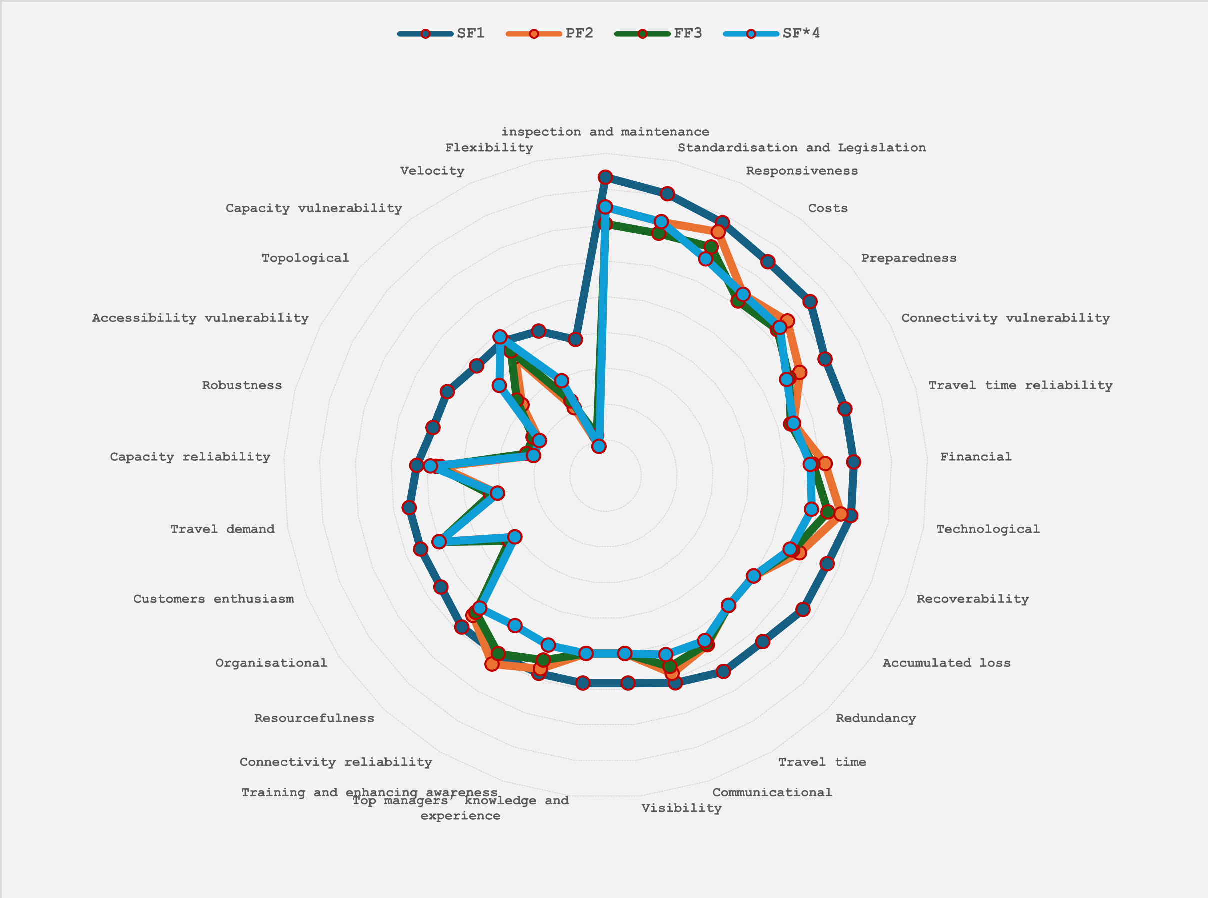

Fig. 7a. SFD score functions comparison.

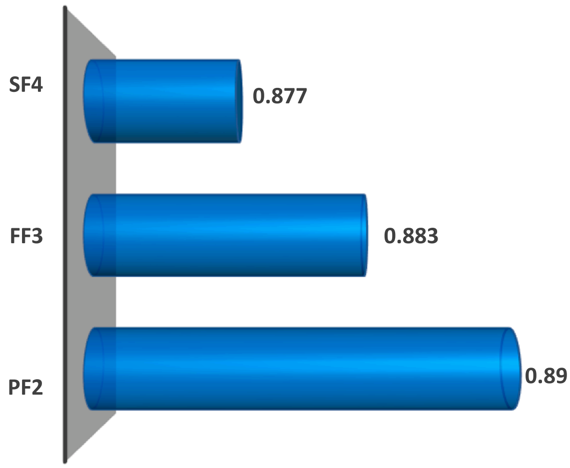

Fig. 7b. Correlation of SFD score function with other possible alternatives.

presented in Appendix 1.

To confirm the extracted cause-effect relationships, our study adopted a comprehensive approach. Initially, we conducted an extensive literature review to identify key factors and establish a solid theoretical base. This thorough review shaped our research design and analysis, ensuring we addressed the critical nuances of the system under investigation. We also collaborated with a panel of domain experts, who provided crucial insights into the causal links among the factors during each research phase. Additionally, we used a triangulation method (Thurmond, 2001) to verify our findings, cross-referencing them with qualitative data (e.g., literature), expert opinions, and empirical evidence. After deriving the results, we revisited the literature to check our findings. Points of agreement and discrepancy were then discussed with expert panels. These experts reviewed the results, including the causal relationships, and endorsed the findings. We further validated these results against empirical evidence, which confirmed their alignment and bolstered the validity of our conclusions. These triangulation processes are comprehensively outlined in the Discussion and Implications sections.

Consequently, as illustrated in Fig. 6, a set of ten finalised factors, namely Preparedness (F_1), Responsiveness (F_2), Recoverability (F_3), Reliability (F_4), Vulnerability (F_5), Financial (F_6), Technological and Communicational (F_7), Standardization and Legislation (F_8), Inspection and Maintenance (F_9), and Functional and Operational Cost (F_{10}) were finalised and subjected to analysis using the SFDANP approach. It is important to highlight that, moving forward, the term "reliability" will specifically refer to travel time reliability, given its predominant focus in this context. Similarly, the term "vulnerability" will denote connectivity vulnerability. Moreover, F_7 encompasses both technological and communicational subfactors. In this phase, expert panels were actively engaged to assess the effectiveness, ineffectiveness, and neutrality of these factors with one another (According to the questionnaire presented in Appendix 3). The gathered opinions were then transformed into spherical fuzzy scores using Eq.2. Subsequently, the resulting matrix was subjected to normalisation through Eq.3, yielding the Total Relation Matrix (TRM) as formulated in Eq.4. The outcome of this process is vividly depicted through the heat map visualisation in Fig. 8.

As mentioned earlier, for SFD, we also computed the results using alternative score functions, including alternative spherical fuzzy, Pythagorean, and Fermatean, without considering neutrality. The outcomes consistently revealed a high correlation. Additionally, we revisited the differences with experts. They reiterated their confirmation that the spherical fuzzy method yielded superior results, attributed to its effective modelling of opinions with fewer limitations. The results are mentioned in Fig. 9.

As shown in Fig. 9, the score function displays a significant correlation with alternative scoring methods, specifically demonstrating correlation coefficients of 0.86 with the Pythagorean fuzzy (PF2) score function, 0.90 with the Fermatean fuzzy (FF3) score function, and 0.96 with the alternative spherical fuzzy (SF4) score function. Similar to SFD, given that all subsequent calculations hinge on the score function, the elevated correlation values assure the model's validity. The strong consensus among scores generated through diverse methodologies underscores the reliability and consistency inherent in the proposed approach.

Moreover, to confirm the results, (i) as previously mentioned, the method chosen was based on the context and data availability, and (ii) we also employed triangulation (Thurmond, 2001). The findings were verified against literature, expert panels, and empirical

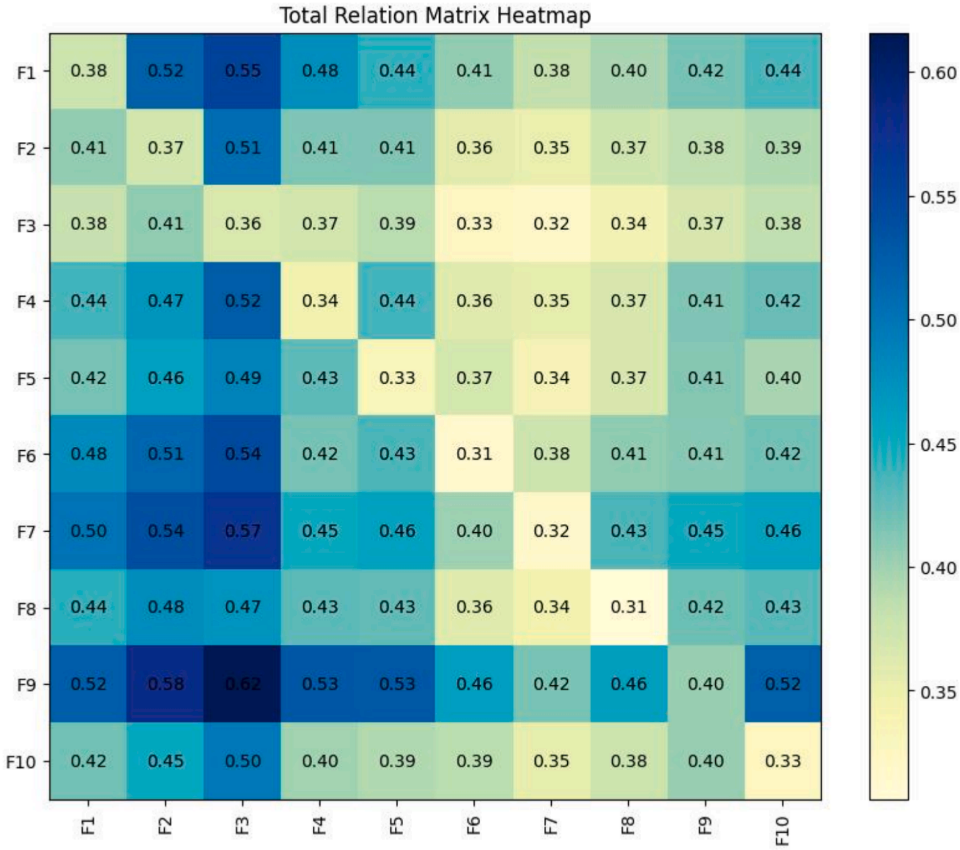

Fig. 8. Total relation matrix heat map.

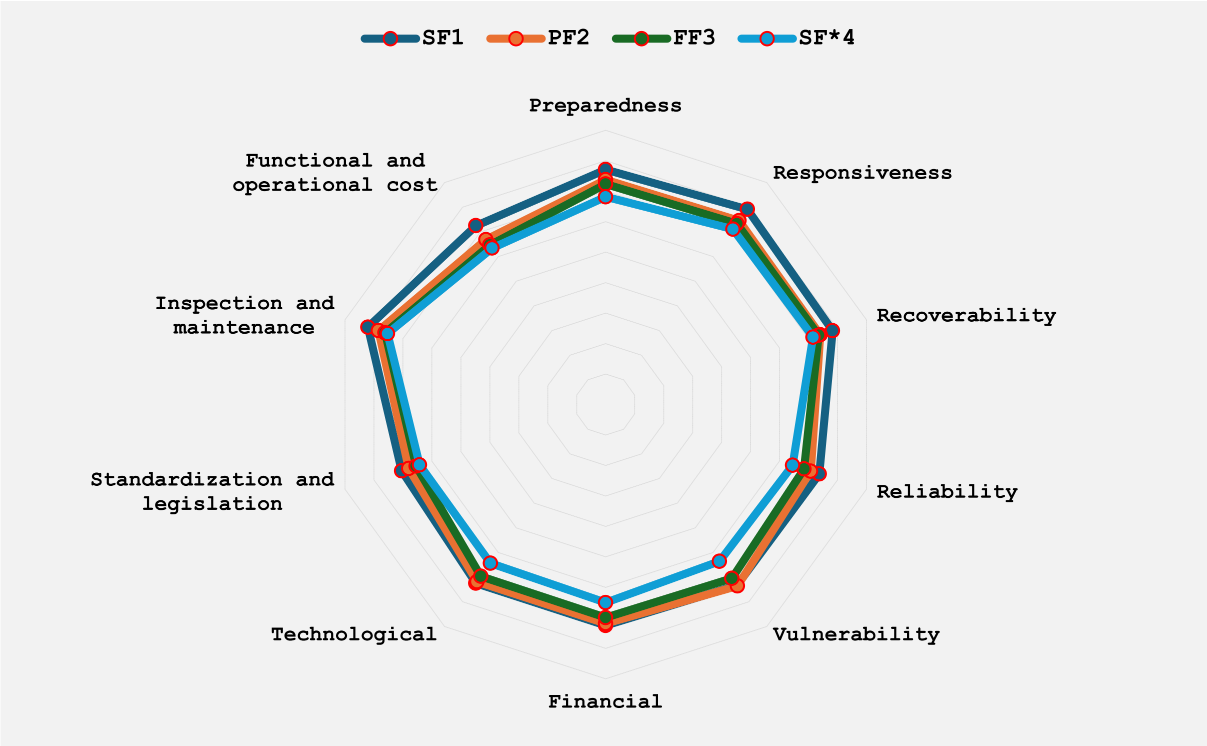

Fig. 9a. Centrality values found on distinct score functions.

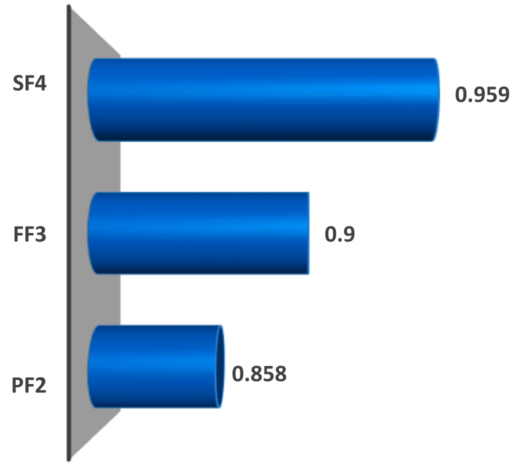

Fig. 9b. Correlation of Centrality values found on distinct score functions.

data. It's crucial to highlight that the cross-verification with expert panels was particularly thorough, featuring several robust discussions to analyse and interpret the results. Ultimately, these were affirmed by the experts. These processes are detailed in the Discussion and Implications section.

After, the causal effects and strengths of the factors were computed. This computation culminated in Fig. 10, which visually portrays the causal values. Within this representation, positive values indicate factors that function as causes, while negative values denote factors that act as effects in the context of the examined relationships. Furthermore, the colour gradient visually encodes the intensity or strength of these causal relationships.

Derived from the TRM, a pivotal threshold of 0.42 has been established. This threshold, computed as the average (i.e., arithmetic mean) of cells within the matrix, is crucial in creating a binary matrix. This binary matrix is the foundation for constructing two distinct networks of relations, representing (i) the global network and (ii) factor-specific connections. The networks are demonstrated in

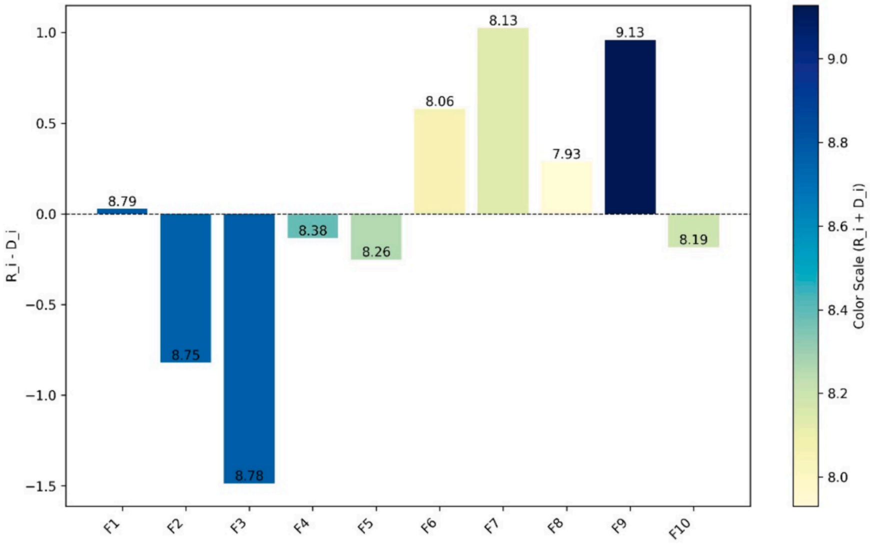

Fig. 10. Cause and effect diagram.

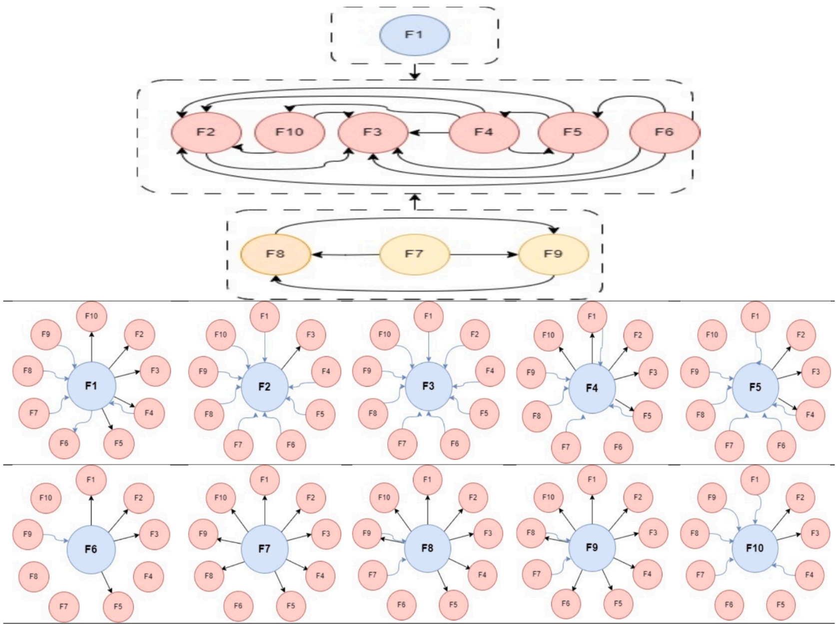

Fig. 11. Factors relations.

Fig. 11.

Ultimately, the weighted supermatrix is meticulously computed following the formulation outlined in Eq.5. The subsequent step involves determining factor weights (Fig. 12) through a limiting process, underscoring the significance of each factor within the overarching framework.

The results of SF-ANP demonstrate the weights of F_1 to F_{10} as w = {0.104, 0.113, 0.121, 0.101, 0.101, 0.089, 0.085, 0.091, 0.097, 0.099}. Therefore, "Recoverability" is the most significant, and "Technological and Communicational" is the least crucial among these critical factors.

5. Discussion and implication

This paper filled a literature vacuum pertinent to resilient international maritime transportation systems by distinguishing resilience factors of the international maritime transportation system by studying one of Asia's low-income countries with a prominent

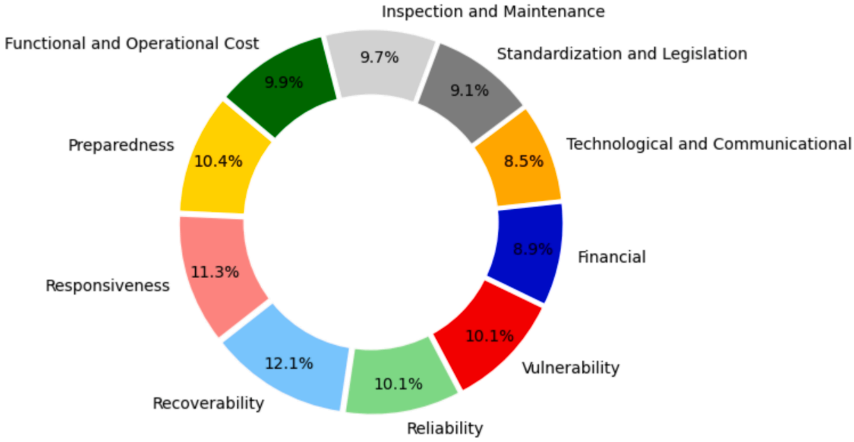

Fig. 12. The weight of international maritime transportation resiliency factors.

geopolitical role in the region (Iran) (Serdar et al., 2022). To this end, a hybrid of SLR and SFD has innovatively been applied. It also investigated the priority of screened factors and cause-and-effect interactions with a spherical fuzzy multi-layer decision-making framework (Nipa & Kermanshachi, 2021). It finally explored the evidence of the impacts of a wide collection of abrupt events on the selected factors (Gu & Liu, 2023). Considering the investigated factors according to the experts' opinions, to check the findings with real-world cases and provide more practical and managerial insights in this research, a list of unexpected events that have occurred since 2000 was extracted from the literature and presented in Table 4. These events have been selected based on their impact on the international transportation system resiliency, especially maritime transportation.

In a focus group that the researchers had with the experts who participated in the primary data gathering stage, the experts unanimously agreed that Iran's maritime transportation system had been influenced by economic events (E_1), war and terrorist attacks (E_4), and the health crisis (E_5) considering the definitions mentioned in Table 4. For instance, E_1 is drastically hurting all economic sectors of Iran, considering the global and USA sanctions (De Rogatis, 2022). Moreover, considering the global coalition to defeat ISIS and the prominent geopolitical role of Iran in the Middle East, E_4 is also crucial (Ghaffarpour & Zamanian, 2022), and so is E_5 because of Covid-19 (Ezzati et al., 2023). The focus group unanimously confirmed that the most important and drastic event among these three events was the first one due to global sanctions. The following policies were common from a long list of solutions adopted by Iranian officials to deal with these unexpected events (De Soyres et al., 2019; Iranian American Studies Center, https://ascenter.ir., 2023).

- Direct Transportation (P_1). Direct maritime transportation system between Iran and the origin or destination points,

Table 4
List of unexpected events.

Type of event	Definition	Reference
Economic event (E_1)	Positive or negative economic reactions from natural and artificial disasters. Such economically influential events that occurred in the 21st century are (I) the Covid-19 pandemic and the 2020 recession, (II) the Brexit vote (Britain's exit from the European Union) in 2016, (III) China emerging as the world's largest economy in 2015, (IV) Japan's tsunami and nuclear disaster in 2011, (V) war on terror in 2001, (VI) sanctions on Iran from 1979 to the present, etc.	(Sen, 2018; Amadeo, 2021)
Weather event (E_2)	Weather and climate events that occurred in the past decades, such as heavy rainfall and flooding, cold winters, storms, hurricanes, snowstorms, heatwaves, drought, etc.	(National Weather Service, 2023)
Earthquakes (E_3)	The Earth's surface shakes due to an abrupt energy liberation in its lithosphere. For instance, the Peru earthquake in 2001, the Maule earthquake in 2010, the Tohoku earthquake in 2011, the Turkey-Syria earthquake in 2023, etc.	(USGS, 2023)
War and terrorist attacks (E_4)	International war and terrorist attacks that occurred in two past decades, e.g., the War in Afghanistan from 2001 to 2014, Iraq War from 2003 to 2011, Libya Conflict from 2011 until the present, Syria Conflict from 2011 to the present, Yemen Conflict from 2014 to the present, Global Coalition to Defeat ISIS from 2014 to the present, Russia-Ukraine war from 2014 until the present.	(Imperial War Museums, 2023)
Health crisis (E_5)	An uphill situation that greatly hits public physical and mental health in one or more geographic areas. For instance, the global outbreak of the Covid-19 virus started in 2019 and has continued until now.	(WHO, 2023)
Accident (E_6)	Different types of maritime accidents have occurred. E.g., offshore oil rig mishaps, cruise vessel mishaps, tugboat accidents; accidents on crude oil tankers and cargo ships, such as explosions; grounding of ships; accidents because of drugs and alcohol; crane mishaps; accidents in shipyards; accidents on diving support vessels; accidents on barges, cargo hauling accidents.	(KaranC, 2019)
Transportation Infrastructure failure (E_7)	An integration of sea level rise, storm surge, heavy downpours, and the pattern of ongoing progress in coastal districts led to maritime transportation infrastructure failure.	(Tonn et al., 2021)

Table 5
The impact of policies on international maritime transportation resiliency factors.

Factors	Policies-Factor Title	Direct Transportation (P1)	Sanctions risk management (P_2)	Aligned Partners (P_3)	Currency Change (P_4)	Identity Management (P_5)
F1	Preparedness	△	●	△	●	△
F2	Responsiveness	◆	△	△	◆	◆
F3	Recoverability	◆	●	◆	△	◆
F4	Reliability	△	◆	◆	△	◆
F5	Vulnerability	◆	◆	◆	◆	●
F6	Financial	◆	◆	◆	◆	◆
F7	Technological and Communicational	△	◆	◆	△	◆
F8	Standardization and Legislation	◆	◆	◆	◆	◆
F9	Inspection and Maintenance	◆	●	◆	△	◆
F10	Functional and Operational Cost	◆	◆	◆	△	◆

- Sanctions risk management (P_2). Incorporating the risk of collaborating with Iran in the maritime transportation insurance agreements,
- Aligned Partners (P_3). Collaborating with origins/destinations with limited political alignment with the USA,
- Currency Change (P_4). Minimising the financial transactions with partners in USD and replacing other popular currencies,
- Identity Management (P_5). Changing, using fake identities, etc., to avoid detention and custody of any partner vessels.

Finally, the focus group analysed the impact of the top five policies adopted by the Iranian international transportation system to overcome the unexpected events discussed in Table 4. They evaluated the impact of the policies according to the ten critical factors extracted in this research on the resilience of the transportation system. The result is presented in Table 5, where low, medium, and high impacts are used for this evaluation.

As Table 5 presents, Sanctions risk management policy (P_2) has the most influential impact on the international resiliency factors with a high impact on (i) preparedness, (ii) recoverability, and (iii) inspection and maintenance. Hence, including the potential hazards of engaging with a sanctioned nation in marine transport insurance contracts is recommended for other similar circumstances. The second recommendable policy is the Currency Change (P_4), with a high impact on preparedness and a medium impact on (i) recoverability, (ii) reliability, (iii) technological and communication, (iv) inspection and maintenance, and (v) functional and operational cost resulting in the resiliency of international transportation systems. Reducing monetary dealings with associates in USD and substituting them with other widely accepted currencies is advisable for other emerging countries facing similar unexpected global events. Recent ideas such as the BRICS currency (Brazil, Russia, India, China, and South Africa) is a starting point for easily implementing this suggestion in the near future (Das and Roy, 2023). By 2035, these new currencies are predicted to be replaced in many international agreements (Sahoo et al., 2023). Moreover, cryptocurrencies and blockchain technologies are supporting and facilitating the implementation of this policy (Wang and Luo, 2023) adopted by Iran's international maritime transportation system. Identity management (P_5) is also the last recommendable policy for similar conditions, with a high impact on vulnerability and a medium impact on preparedness, resulting in the resiliency of international maritime transportation systems. Consequently, adopting and utilising false identities to evade the apprehension and holding of partnerships proved an effective strategy. However, industry 4.0 technologies and building blocks such as blockchains might detect these false and fake identities in international transportation (Das et al., 2023).

Employing fictitious identities is neither lawful nor ethical and represents a contentious approach within international maritime operations. Notwithstanding, as detailed in the manuscript, this tactic is currently being utilised by Iranian maritime logistics, a strategy endorsed by the "Research Center of the Islamic Legislative Assembly[1]" (De Soyres et al., 2019; Iranian American Studies Center, https://ascenter.ir., 2023). Given that the bulk of Iran's maritime logistics involves the transportation of oil, gas, and other natural resources—which constitute a significant portion of Iran's exports and gross domestic product—it appears that certain unethical and illicit methods have been adopted to ensure the provision of a basic level of service to the populace. This raises a pertinent question regarding the ethical and humanitarian implications of political and economic sanctions (Peksen, 2019). Consequently, it has been observed that such political sanctions have predominantly impacted sectors such as medicine and healthcare services, as well as the economic and financial conditions of the general public, without effectively hindering Iran's nuclear initiatives (Maloney, 2015; Dizaji, 2021).

Keeping the resilience cycle of maritime transportation (Fig. 1) and results (Fig. 6) in mind, Iran's international maritime transportation system mainly emphasises preparedness, travel time reliability, inspection, and maintenance in the ex-ante preparation

[1] https://rc.majlis.ir/fa/law/show/95589.

stage. During a perturbation, the potency of responsiveness and recoverability are employed to offset connectivity vulnerability. In an ex-post preparation stage, preparedness has again been highlighted. Jointly, financial, technological, and communicational resources, along with standardisation and legislation, are mainly employed to compensate for both adaptability and low performance caused by a perturbation (Deveci et al., 2023). Iran is a low-income country, and expectedly, functional, and operational costs have been more controlled in each resilience phase (Bwambale et al., 2023). According to the extant literature, such common factors have rarely been considered in other resilient maritime transportation systems. However, some resilience dimensions are neglected by Iran compared to others. For instance, Iran should consider redundancy and connectivity reliability before a disaster to mitigate connectivity vulnerability during an unexpected event. Besides, being agile and robust are two weak points of Iran's international maritime transportation system in reducing vulnerability. Finally, after a disruption, its flexibility should be upgraded to even benefit from the post-impact of the crisis (Gu & Liu, 2023).

Furthermore, the weight of the available resilience factors (Fig. 12) indicated that Iran's international maritime transportation system has mainly paid for time and cost to be adaptable during turbulence. However, preparedness is a third priority. Consequently, resilience during a disruption is more prominent in Iran than in the ex-ante and ex-post. However, benchmarking the developed countries indicated that the system's strength in the ex-ante preparation stage leads to efficiently being more resilient during and after a disruption (Cimellaro et al., 2021; Tonn et al., 2021). This path can be paved in Iran using the cause-and-effect diagram (Fig. 10) and interaction framework (Fig. 11). Generally, Iranian experts have recognised as causes the resilience factors mainly applied in the ex-ante preparation stage. Conversely, all the resilience dimensions employed during turbulent events form the effects. To avoid a sharp reduction of transportation performance resiliency during a disruption, policymakers of Iran's maritime transportation should focus more on resilience factors that are not currently prioritised.

More practically, improving reliability, inspection and maintenance, standardisation and legislation, and financial, technological, and communicational resources can progress preparedness (Deveci et al., 2023). These are the main causes of extraordinary performance during a crisis as they impact recoverability, responsiveness, vulnerability, costs, and reliability (Cimellaro et al., 2021; Tonn et al., 2021). Besides, well-controlled costs associated with preparedness activities, reliability, technology, standardisation, and maintenance are adaptability guarantees during and after a disruption (Bwambale et al., 2023). Moreover, inspections and maintenance work consume significant financial resources (Dui et al., 2021). Well-applied technologies and standardisation could control costs (Deveci et al., 2023). Therefore, reliability would also be improved, minimising vulnerability during an unexpected event (Serdar et al., 2022).

Interestingly, Persian Gulf with an area of 240,756 Km^2 includes eight countries: Iran (97,860 km^2), United Arab Emirates (52,455 km^2), Saudi Arabia (33,792 km^2), Qatar (31,819 km^2), Kuwait (11,786 km^2), Bahrain (8,826 km^2), Oman (3,678 km^2), and Iraq (540 km^2) (Wikipedia, 2023). Fortunately, this territory covers 5,117 coastline lengths [Iran: 1,536, Saudi Arabia: 1,300, United Arab Emirates: 900, Qatar: 563, Kuwait: 499, Bahrain: 161, Oman: 100, and Iraq: 58] (Wikipedia, 2023). Similarly, these countries earn their main income from exporting crude oil and petroleum products by maritime transportation. To this end, these countries have at least one important seaport that is prominent for international container shipping transportation (Barman, 2023). Hence, other Persian Gulf countries and Iran could benefit from these research results due to geographical analogies. Particularly, *"Iran and Saudi Arabia have much in common. They are both major powers of the eastern Middle East – the two largest countries by area. They are significant oil producers and have two of the largest oil reserves in the world."* (University of Cambridge, Faculty of History, 2021). To increase generalisation potential, some experts who participated in this research experienced working in subsidiaries of the Islamic Republic of Iran Shipping Lines (IRISL) located in the Persian Gulf countries such as Oman and UAE.

Ultimately, the advanced methodology framework described in this paper is versatile enough to be applied to other regions. However, the findings from phases II and III of this study may be influenced by the unique characteristics of the case study. The SLR is a scientific method that extracts research items based on existing literature and is not impacted by external factors. Moreover, uncertainty is a common feature of any environment, and the spherical fuzzy set is useful in all cases. The SFD method is an updated approach suitable for screening research items based on expert opinions. Additionally, the SFDANP is a well-established multi-layer approach that measures interactions and weights of factors based on expert opinions. The selection of resilient factors, along with their network relationships and weights, is influenced by expert opinions and regional circumstances. For example, in countries like China, with standardised high-tech international transit and sufficient funding and experience, some resilient factors like financial, technological, and standardisation may not be considered the most significant (Fu et al., 2018). Vulnerability and recoverability may also not be highlighted as the ranked elements. Therefore, this paper's methodology framework and findings are accurate for use in Iran and similar countries. Nonetheless, some components, such as the framework and the initial list of categorised resilient factors, can be used for other regions unaffected by different conditions.

6. Conclusion

This article deeply investigated 51 relevant research on resiliency factors of transportation systems under uncertainty. As a result, 12 factors and 22 subfactors were extracted and illustrated in Fig. 4. Subsequently, ten crucial factors were further analysed using a novel SFD method and employing Iranian experts, officials, and activists in the international maritime transportation system. Next, by developing a novel spherical fuzzy DEMATEL, the cause–effect relationships among the factors were determined and demonstrated in Figures 8 and 9. Eventually, the importance of each critical factor was measured via spherical fuzzy ANP and presented in Fig. 12. The most unexpected events since 2000 have been extracted from the available literature. The impact of each event on the Iranian international maritime system was also discussed, and the policies that Iranian officials have adopted were debated regarding the critical factors.

This research has limitations in terms of data gathering and data analysis. From the first perspective, this article applied secondary data for the SLR section and primary data for the spherical fuzzy Delphi, DEMATEL and ANP. Themes, factors and subfactors could have emanated from structured or semi-structured interviews with the same experts, officials, or activists in the resilience transportation system. Hence, other scholars could extract the initial list of factors from primary data and interviews and then benchmark them with the results of the literature review shared in this research. Furthermore, the primary data collated in this research was limited to the opinions of experts from the Iranian international maritime system. Although the Iranian maritime transportation system plays a vital role globally, for more generalisable outcomes, other scholars could benefit from other experts in other countries or other transportation sectors to compare the findings. Overall, future research could validate how this paper's findings are generic enough to apply in other Persian Gulf countries, particularly those without economic and political sanctions, contributing to the separation between the fundamental resilient and collaboration-related factors.

From the second perspective, this article developed two novel decision-making frameworks to screen factors, analyse their relationships, and determine their importance. As this article considers unexpected events and environmental uncertainty, spherical fuzzy values were employed and incorporated within Delphi, DEMATEL and ANP. Nevertheless, other uncertainty values (e.g., Fermatean fuzzy and Pythagorean fuzzy) could be replaced and developed by other scholars. However, spherical fuzzy is relatively new and provides meaningful results. Moreover, instead of using DEMATEL to evaluate the relationship among the factors, other methods, such as interpretive structural modelling or cognitive mapping, could be replaced or mixed with DEMATEL for robust outcomes.

CRediT authorship contribution statement

Hannan Amoozad Mahdiraji: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Fatemeh Yaftiyan:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Formal analysis, Data curation. **Aliasghar Abbasi-Kamardi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Formal analysis, Data curation. **Demetris Vrontis:** Writing – review & editing, Writing – original draft, Validation, Resources, Project administration, Investigation. **Yu Gong:** Writing – review & editing, Writing – original draft, Software, Resources, Project administration, Investigation.

Data availability

Data will be made available on request.

Appendix 1. – Fuzzy extensions score functions

Pythagorean Fuzzy sets. Pythagorean fuzzy sets (PFS) extend classical fuzzy set theory by incorporating the notion of indeterminacy through a membership degree and a non-membership degree. The initial formula of a Pythagorean fuzzy set, denoted. The basic definition involves two parameters: the membership degree $\mu_A(x)$ and the non-membership degree $\upsilon_A(x)$ which are defined within the unit interval [0,1]. Pythagorean fuzzy condition ensures that the sum of their squares of membership and non-membership is less than 1 ($\mu_A(x)^2 + \upsilon_A(x)^2 \leq 1$), emphasising the uncertainty inherent in real-world decision-making scenarios (Huang et al., 2020).

Let $X = \{x_1, x_2, \cdots, x_n\}$ represent a Universe of Discourse. Then, a Pythagorean Fuzzy Set (PFS) P on X is defined as $P = \left\{(x, \mu_P(x), \upsilon_A(x))\, where \mu_P(x), \upsilon_A(x) \in [0,1], \mu_A(x)^2 + \upsilon_A(x)^2 \leq 1\right\}$. The score of a Pythagorean fuzzy set is computed via $\mu_A(x)^2 - \upsilon_A(x)^2$ (Zhou and Chen, 2019).

Fermatean Fuzzy sets. In conjunction with Pythagorean fuzzy sets, Fermatean fuzzy sets expand upon classical fuzzy set theory by also applying the concept of indeterminacy through both a membership degree $\mu_A(x)$ and a non-membership degree $\upsilon_A(x)$ each constrained within the unit interval [0,1]. Fermatean Fuzzy limitations ensure that the sum of their cubed values for membership and non-membership remains below 1 ($\mu_A(x)^3 + \upsilon_A(x)^3 \leq 1$). This approach reflects the nuanced treatment of uncertainty inherent in Fermatean fuzzy sets, offering a comprehensive framework for handling imprecision in decision-making scenarios (Sahoo, 2021).

Let $X = \{x_1, x_2, \cdots, x_n\}$ represent a Universe of Discourse. Then, a Fermatean Fuzzy Set (FFS) F on X is defined as $F = \left\{(x, \mu_F(x), \upsilon_F(x))\, where \mu_F(x), \upsilon_F(x) \in [0,1], \mu_F(x)^3 + \upsilon_F(x)^3 \leq 1\right\}$. The score of a Fermatean Fuzzy set is computed via $\mu_A(x)^3 - \upsilon_A(x)^3$ (Zhou and Chen, 2019).

Spherical Fuzzy Score Function. Furthermore, in addition to the score function delineated in the methodology section, an alternative score function tailored for spherical fuzzy sets has been formulated as $(\mu_A - \pi_A)^2 - (\upsilon_A - \pi_A)^2$ (Kutlu Gündoğdu and Kahraman, 2019). In our study, we have incorporated this distinct score function alongside the PF and FF scores. This inclusion aims to facilitate a comparative analysis of results by incorporating the unique characteristics captured by the spherical fuzzy set score function utilised in this research. Such a comprehensive approach allows for a thorough evaluation of the outcomes, considering multiple perspectives and methodologies.

Appendix 2. – SFD questionnaire

Thank you for your valuable contribution. We are researching to improve the resiliency of transportation systems under uncertainty, a challenging global issue that requires careful consideration and understanding. Your expertise in this field is highly appreciated, and your insights will be crucial to the success of this study. In this questionnaire, we have identified 29 resilience factors related to transportation systems. Your task is to assess the significance of each factor by assigning a value on a linguistic scale. Please indicate your level of neutrality, agreement (availability), or disagreement (unavailability) for each factor by selecting one of the following linguistic terms (Corresponding numerical values {Not = 0, Low = 0.25, Pretty = 0.5, Very = 0.75, Absolutely = 1}). To maintain the accuracy and integrity of the responses, please note that the sum of the squares of your ratings in each row should not exceed 1, as demonstrated in the accuracy column. Thank you once again for your time and expertise.

Resiliency Factor	Definition	Neutrality	Availability	Unavailability
Flexibility	The system's potency to cope with, resolve, or even benefit from perturbations, particularly by resource reconfiguration. Regarding transportation systems, "flexibility can be used to describe the capacity of a system to handle and absorb changes and to emphasise the ''changes' on the demand side". It means the capacity to adapt to market changes and the allocation of resources. It is essential for the post-disruption phase. In contrast to robustness, flexibility persists to withstand or sustain changes by disturbance instead of adapting to them.			
Robustness	Reflects the transportation system's resistance to disruptions. Hence, it refers to this system's strength in enduring, absorbing, or adapting to disturbances while continuing its operations. Robustness is a crucial resilience factor exactly during a disruption.			
Preparedness	Reflects the transportation system's ability in the readiness phase (before an unexpected event) when it tries to prepare for an unexpected event (emergency preparedness and response preparedness) by employing prominent proceedings, e.g., anticipation, monitoring, and learning.			
Responsiveness	Indicates the transportation system's capability in the response phase when it attempts to respond to the perturbation by employing prominent actions.			
Recoverability	Presents the potency of the transportation system in the recovery phase; when it intends to timely amend the disrupted system after the turbulence by employing prominent measures, it is noteworthy that the considered system may have to build a completely new system in this phase. It is acknowledged as a critical indigent of safe and efficient shipping networks.			
Velocity	Refers to the rapidity of the transportation system to be recovered after an unexpected event that greatly hits the demand–supply cycle. It refers to recovering functions as soon as possible in a timelier manner.			
Visibility	Reflects transparent traceability of inventory management, demand–supply cycle, scheduling, etc. Additionally, it indicates visibility and trust in communication and information sharing.			
Redundancy	Reflects the transportation systems' strength in operating while some ingredients are missing, owing to extra valency of talents, materials, etc., at potential pinch points. For instance, "In this case, redundancy usually appears as the existence of optional routes between origins and destinations." the capacity of the maritime system to take some contingency measures to keep its overall performance exactly during a disruption. E.g., duplicating the prominent operations of the system and applying backup functional modules like more alternative routes.			
Resourcefulness	Refers to the transportation system's ability to mobilise internal and external resources, such as human capital, materials, budget, etc., to help the system recover actions in facing disruptions during a recovery phase. Resource accessibility and prioritising are two prominent elements in this regard.			
Connectivity reliability	Indicates "the probability of the nodes in a transportation network remaining connected".			
Travel time reliability	Presents "the probability of reaching a destination within a given travel time".			
Capacity reliability	Denotes "the probability of whether a network can satisfy a specified demand under degraded network condition".			
Connectivity vulnerability	It is a negative feature that calculates connectivity reduction based on specified topology indicators			
Capacity vulnerability	It reflects capacity pinch, which leads to grid disruption with insufficient capacity			
Accessibility vulnerability	It refers to weakness in accomplishing apparent chances, such as travel costs stemming from traffic assignments to provide network efficiency and effectiveness			
Financial	Reflects liquidity volume and fund accessibility in promoting transportation system performance in the case of unexpected events. In this respect, two subjects of type and case of investment form critical decisions. For instance, investment in preventive processes is one of the best choices.			
Technological	Reflects creating innovation and utilising advanced technologies, e.g., shared vehicles, drones, robotics, Internet of Things, and blockchain, to enhance the			

(continued on next page)

(*continued*)

Resiliency Factor	Definition	Neutrality	Availability	Unavailability
	transportation system performance in case of perturbations. For instance, "data sharing between vehicles and infrastructure" is an innovative action to do so.			
Topological	Refers to transportation network connectivity, viz. accessibility, which emphasises the arrangement of nodes and links, particularly their locations and the nature of their connections. Focusing on two types of international and local connectivity is essential.			
Communicational	In case of a perturbation, real-time data, knowledge, and information sharing are critical elements of a resilient transportation system. To this end, a disaster database will help perform prevention actions. Besides, integration and collaboration with external partners and relevant authorities is another communicational infrastructure to deal with it.			
Organisational	Some characteristics such as teamwork, promoting organisational culture, self-organisation, re-engineering, etc., can be useful for a transportation system to cope with an unexpected event.			
Top managers' knowledge and experience	Reflects the top managers' knowledge and experience in previous crises when managing a transportation system.			
Customers enthusiasm	Reflects the degree of importance of safety issues from the customers' mindset, which makes them enthusiastic to pay costs for extra safety and sanitary options. This also impacts their demand pattern.			
Standardisation and Legislation	Refers to the vital standards and laws crucial for managing proactive safety and security. For instance, particular standards and rules for reforming the workforce, performing formal processes, safety supervision guidance, etc.			
Training and enhancing awareness	Reflects the necessity of holding appropriate training courses for human capital related to safety and security issues, facing disasters, etc. This leads to human resource awareness and promoting safety, disasters, etc.			
inspection and maintenance	Refers to carrying out ordered and precise checks on the daily operation of human resources and devices. Which stem from a coherent plan of maintenance and repair.			
Travel demand	Refers to the flow of passengers or freight volume that should be transferred.			
Travel time	It is a scale of the time necessary to travel from the current place to the destination.			
Costs	Reflects different costs (e.g., operational costs, expected failure costs, travel costs) that the transportation system must bear.			
Accumulated loss	Refers to the annual losses left undistributed, which have not been debited to the partner's capital account.			

Appendix 3. – SFDANP questionnaire

Thank you for your valuable contributions. In the questionnaire below, please help us determine how each factor in the rows affects the factor in the columns. Please indicate the Effectiveness, Ineffectiveness or if you have a neutral opinion. Corresponding numerical values are {Not = 0, Low = 0.25, Pretty = 0.5, Very = 0.75, Absolutely = 1}). To maintain the validity and integrity of the responses, please note that the sum of the squares of your ratings should not exceed 1, as demonstrated in the validity column. Thank you once again for your time and expertise.

Factors	Preparedness			Responsiveness			… (Repeated for other factors)		
	Effectiveness	Ineffectiveness	Neutrality	Effectiveness	Ineffectiveness	Neutrality	Effectiveness	Ineffectiveness	Neutrality
Preparedness									
Responsiveness									
Recoverability									
Reliability									
Vulnerability									
Financial									
Technological									
Standardisation and Legislation									
Inspection and maintenance									
Functional and operational cost									

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