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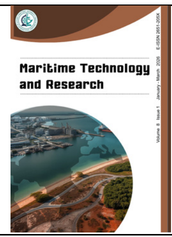

Research Article

Ranking barriers to green port development: A neutrosophic-fuzzy ISM approach

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Abstract

Green ports represent a critical evolution in maritime logistics, transforming traditional seaports into environmentally conscious hubs that balance operational efficiency with sustainability. This study investigates the complex barriers hindering green port implementation using a hybrid neutrosophic-fuzzy Interpretive Structural Modeling (ISM) approach. Ten experts from port management, operations, and environmental fields gave their opinions. The study used a special neutrosophic fuzzy scale to measure unclear and uncertain expert views on 15 barriers. Results show that financial availability (FA) and high initial cost (HIC) are the biggest problems. FA scored a truth value of 0.94 and falsity of 0.06, making it the top concern. Regulatory complexity (RC) also matters, but has more uncertainty. Technical problems like lack of capacity (LTC) and technology readiness barriers (TRB) have mixed effects depending on context. Driving-dependence analysis puts FA, HIC, and RC as the main drivers, while LTC acts as a linkage barrier. Monte Carlo sensitivity tests prove the model is stable, confirming financial and regulatory barriers as priorities. This framework helps port leaders understand how barriers relate and where to invest. It supports closing the gap between green port goals and real implementation, aiming for ports that support both the economy and the environment.

1. Introduction

Maritime activities play a crucial role in global trade, economic development, and cultural exchange. Maritime industries, including fishing, shipping, shipbuilding, and offshore energy, provide employment and contribute significantly to national economies (Bui & Nguyen, 2021; Nguyen et al., 2024; Quy et al., 2025; Vakili et al., 2022). As the world becomes more interconnected, the strategic and environmental importance of maritime activities continues to grow, making the protection and sustainable use of maritime resources more important than ever (Novitasari & Anwar, 2022; Vu et al., 2024). Green ports represent an essential paradigm shift in maritime logistics, where conventional seaports evolve into environmentally conscious infrastructure nodes (Lam & Notteboom, 2014; Pham et al., 2023; Sharif et al., 2023). Conventional seaports are slowly transforming into places that are environmentally conscious, while still maintaining their profitability (Le et al., 2023). A key example is the shore power system (cold ironing), which enables ships to shut down their engines and draw electricity from the grid, thereby reducing emissions of sulfur oxides, nitrogen oxides, and noise pollution (Abu Bakar et al., 2023; Hoang et al., 2022, 2023). This way, emissions are reduced not just in the port, but also in places where electricity is generated. Many green ports also put solar panels on roofs or land near facilities, and they replace old lights with LED ones. Cranes, trucks, and other machines are also going electric (Aksoy & Durmusoglu, 2020; Żukowska, 2020). Hybrid or full electric vehicles save fuel and lower pollution (Nguyen et al., 2021). Now, ports also use smart techs like IoT, real-time data, and AI to manage ship traffic and reduce waiting times (Alamoush & Ölçer, 2025; Tan et al., 2025). Altogether, these improve the air around the port, make work safer, and keep nearby people healthier (Pavlic et al., 2014; Satta et al., 2025).

Still, even with all this, converting the conventional ports into green ports is quite a challenging task. The first problem is the very high cost at the beginning to build a new system or to upgrade old ones. Aspects like shore power need expensive wires and electric stations and sometimes need improved roads. Small ports or ports in less developed places do not always have this high level of finance or investment (Feng et al., 2022; Fratila et al., 2021). They need help from the government or private groups to initiate and sustain this change. Then, there remains a high level of uncertainty on the policy paradigm in this domain. Different types of electric standards, multiple government approvals, and paperwork slow progress. Green port development can be challenging in cases when such approvals take years. This also keeps private companies from investing in such infrastructure projects (Lee & Nam, 2017; Notteboom & Lam, 2018). Another concern is that those employed at ports may lack the knowledge to operate or maintain the new technologies. Training is essential for those engaged in operations, maintenance, or management. A further difficulty is the ambiguity regarding return on investment. Shipping businesses may be uncertain about potential cost savings. Moreover, other fuels such as hydrogen or LNG present distinct issues. They may be expensive, difficult to store, or hazardous in the absence of safety mechanisms. This renders the selection of a long-term fuel ambiguous (Balbaa et al., 2019). Some ports also have old electric grids that cannot support new green systems. Therefore, they either need stronger grids or backup battery systems to keep things running smoothly. The other important barrier that affects green port implementation is the reluctance shown by the local community. People who live near ports might not like big changes, as they are concerned with job losses and the local economy. The senior port management must create a consensus to show benefits clearly and involve them in plans (Alamoush et al., 2023). Also, many ports do not have good systems to track their emissions and energy. Without proper data, it is hard to ascertain which approach among the options available is more effective. This makes it tough to convince others or obtain funding. This study's intention is to explore how these barriers connect. It uses an approach called the hybrid neutrosophic-fuzzy ISM method. The traditional ISM elucidates the causal relationships between problems, while fuzzy logic quantifies the strength of such connections (Thakur & Wilson, 2024). The neutrosophic aspect addresses ambiguous and uncertain responses provided by experts. Experts use this strategy to provide insights into the interdependencies of barriers, subsequently constructing a model to illustrate their relationships and hierarchies. This also illustrates which restrictions are primary causes and which arise thereafter (Kilic et al., 2021; Nazarian-Jashnabadi et al., 2023). The ultimate contribution of this research lies in bridging the gap between green port planning and implementation. The proposed paradigm clarifies barrier interrelationships, offering actionable insights for prioritizing investments, formulating targeted policies, and facilitating informed decision-making. This approach views ports as hubs of commerce and as drivers of climate initiatives, social equity, and sustainable regional advancement.

2. Materials and methods

2.1 Barrier identification

Ports are increasingly being called upon to transform into environmentally responsible gateways that support sustainable maritime logistics and protect surrounding communities. The idea of a green port includes using clean energy, cutting down on emissions, and running things more efficiently, but there are still many problems that stand in the way of making these happen. These problems include high initial expenses, technology restrictions, inefficient administration, and hostility from those who work at ports. Identifying and comprehending these limits is crucial, since it enables the planning of actions and the allocation of targeted investments. **Table 1** below lists fifteen important barriers, each with a clear acronym and short description. This will help with organized analysis and smart planning for green port development.

Table 1 Barriers identification for green ports.

Barrier Name	Abbreviation	Explanation
High Initial Cost	HIC	This barrier refers to the substantial upfront investments needed for infrastructure, equipment, and renewable technologies in ports. Studying it is essential because financial constraints often determine whether green initiatives are viable. Addressing HIC is fundamental to unlocking sustainable transformation, especially for smaller or resource-limited ports (Lee & Nam, 2017; Oniszczuk-Jastrząbek et al., 2018).
Regulatory Complexity	RC	RC covers overlapping standards, slow consent processes, and inconsistent regulations across jurisdictions. It is important to study because regulatory uncertainty can stall projects and discourage investment. Simplifying RC is key to accelerating the deployment of green infrastructure (Lam & Notteboom, 2014; Nguyen et al., 2022).
Technology Readiness Barriers	TRB	TRB shows how well a port's environment can support emerging technology. Some important contexts are the capacity of the grid and substations for electrified assets; how well they work with existing standards and shore power interfaces; and the availability of certified vendors and lifecycle maintenance. When grids are strong, standards are consistent, and vendors and IT integration are advanced, readiness increases and deployment risk decreases. On the other hand, broken standards, poor cyber practices, and tariffs that do not match up slow down commissioning, lower uptime, and hurt the business case (Guo et al., 2021; Zhang et al., 2024).
Stakeholder Commitment Constraints	SCC	SCC includes insufficient involvement of communities, operators, governments, and non-governmental organizations (NGOs) in green initiatives. Studying SCC is vital because cooperative planning reduces resistance and builds trust. Overcoming SCC fosters smoother adoption and shared ownership of green port strategies (Di Vaio & Varriale, 2018; Nusraningrum et al., 2023).
Lack of Technical Capacity	LTC	LTC refers to gaps in skills, training, and knowledge necessary for operating and maintaining new systems. Evaluating LTC is important because capacity deficits can undermine project outcomes. In ports with skilled technicians, clear standard operating procedures (SOPs), and established vendor partnerships, new systems ramp faster and achieve planned performance. Where skills, training pipelines, and maintenance frameworks are thin, even funded technologies face delays, higher O&M (Operations and Maintenance) costs, and more frequent downtime. Resolving LTC ensures ports sustain green technologies effectively (Parhamfar et al., 2023; Wang et al., 2023).
Land and Right-of-Way Availability	LRA	LRA denotes existing installations designed for traditional operations that resist retrofit. This matters because retrofitting can be costly, complex, and disruptive. Space constraints for substations, cable routes, and Onshore Supply of Power (OPS) gear can cause redesigns and delays; early site safeguarding, joint trenching, and compact equipment choices de-risk layout conflicts. Overcoming LRA is critical for seamless integration of green upgrades (Issa Zadeh et al., 2023; Twrdy & Zanne, 2020).

Table 1 (continued) Barriers identification for green ports.

Barrier Name	Abbreviation	Explanation
Financing Availability	FA	FA addresses access to loans, grants, subsidies, or private funding for sustainable projects. Studying FA is essential since a lack of capital access can halt initiatives before they start. Ensuring FA opens the door to scalable and predictable green investments (Camargo-Díaz et al., 2022; Dai et al., 2019).
Information Flow	INF	Barriers to information flow (INF) cover the absence of reliable systems to measure emissions, energy use, and ecological impact. This study is important because, without accurate data, ports cannot optimize or validate green performance. Addressing INF barriers ensures transparent progress and continuous improvement (Chen, Zheng, et al., 2019; Elhussieny et al., 2023).
Grid Readiness Delay	GRD	GRD refers to limitations in local electricity grids to support high-power shore systems. This matters because insufficient or unreliable grid infrastructure can disrupt green operations. Strengthening GRD is necessary to ensure stability and energy security (Dai et al., 2019; Elhussieny et al., 2023).
Staff Training and Institutional Capacity	STI	Insufficient training pipelines, change management, and data literacy impede adoption; competency frameworks, simulation-based training, and cross-functional governance improve reliability and operational discipline. Ensuring a robust STI plan implementation is crucial to embed sustainability in port culture (Peoples et al., 2022; Teng et al., 2017).
Standardization and Standards Gaps	SST	Non-harmonized connectors, communications, and safety protocols create vendor lock-in and interoperability issues; adopting common standards lowers integration effort, ensures multi-vendor competition, and protects future upgrades. Addressing SST reduces inefficiencies and implementation failures (MdSapry, 2020; Yakan Dündar, 2020).
Sustainability of Alternative Fuel	SAF	Ports face uncertainty around fuel pathways, safety, and readiness for LNG, methanol, ammonia, hydrogen, and advanced biofuels. Some of the most important challenges include bunkering infrastructure, following ISO/IMO requirements, lifetime emissions, vessel compatibility, and emergency response. Clear rules, staged pilots, verified handling standards, and agreements with suppliers lower risk and make it possible to prepare for long-term decarbonization in an achievable way (Bojić et al., 2021; Chen, Zheng, et al., 2019).
Local Market/Industry Readiness	LMI	Limited local vendors and spares logistics extend downtime and costs; vendor development, framework contracts, and regional service hubs improve responsiveness and lifecycle support. This matters because poor coordination can fragment efforts and duplicate costs. Improving LMI ensures cohesive planning and resource optimization (Elentably, 2015; Taljaard et al., 2021; Varese et al., 2022).
Onshore Supply of Power	OSP	Berth compatibility, ship call patterns, connection time, and tariff structures determine utilization; standardized interfaces, synchronized schedules, and fair, predictable tariffs enhance the OSP and emissions impact. Addressing OSP promotes ports that are both green and socially responsible (Lam & Li, 2019; Roh et al., 2016).
Corruption and Governance	CPG	CPG includes opaque decision-making, bribes, and inconsistent enforcement that can undermine green investments. This matters because weak governance can divert funds and erode stakeholder trust. Strengthening CPG is essential for transparency and sustainable progress (Chen, Huang, et al., 2019; Jugović et al., 2022).

2.2 Data collection from domain expert

The primary data collection for this study involves engaging ten domain experts through structured interviews. One expert was a lecturer in marine engineering, one was a lecturer in port operation, three were mid-level port managers, and two were junior-level managers working in the port operation domain. Two experts handled cargo at the port. One was an environmental engineer working at the port. These people have firsthand experience with the problems that come with developing green ports. Using a neutrosophic fuzzy scale, which includes the dimensions of truth, indeterminacy, and falsehood, each identified obstacle will be evaluated. This scale is good at capturing expert assessments that are naturally unclear or uncertain. The methodological design comprises making a structural self-interaction matrix, which shows how all potential pairs of barriers are related to each other and how they affect each other. Using these inputs, a neutrosophic fuzzy reachability matrix is made to measure the direction and intensity of effect. This makes it possible to describe the complicated interactions between the obstacles in a systematic way.

2.3 Neutrosophic-fuzzy approach

The neutrosophic-fuzzy method is a hybrid approach that can handle both uncertainty and vagueness in expert opinion. It combines fuzzy set theory and neutrosophic logic to better deal with real-world decision problems where data is not always clear. In several practical scenarios, such as green port planning, experts do not consistently provide optimal solutions. At times, they are uncertain or do not totally concur. This strategy assists in managing such situations. The fuzzy set was initially developed to address incomplete truth. It provides values ranging from 0 to 1 (Ye, 2013). For example, if a barrier is important, an expert may assign a value of 0.7 in terms of importance. However, the fuzzy technique only indicates the degree of truth of a statement; it does not mention any question or perplexity. This is where neutrosophic logic is applicable. It incorporates three components into each judgment- truth (T), indeterminacy (I), and falsehood (F). Each value ranges from 0 to 1, and they do not need to sum to 1. For instance, an expert may assert that a barrier is 0.6 true, 0.3 uncertain, and 0.2 false (Kutlu Gündoğdu & Kahraman, 2019). This approach offers a comprehensive overview of what experts really think. When using this in a decision model, experts rate each barrier using words like high, medium, or low. These words are converted into neutrosophic-fuzzy numbers. Then, for each pair of barriers, the interrelation is estimated. This leads to the formation of a reachability matrix. In that matrix, each value shows how much one barrier affects another. Sometimes a threshold is used to remove small influences and focus on strong ones. After this, a hierarchy is made to show which barrier is the root cause and which one is just an effect (Biswas et al., 2016; Peng et al., 2016). This method is very helpful when experts give different or unclear opinions. It keeps the confusion part of the data and does not ignore it. It also gives a more detailed structure of the problem, which helps the decision maker take better steps. Especially in fields like port sustainability or energy planning, where many factors are involved, this method is useful. In summary, a neutrosophic-fuzzy system is not just better than fuzzy or simple models; it is also closer to real human thinking. It allows for some doubt, some truth, and some error all in one judgment. This makes it a good choice for complex and unclear decision problems.

2.4 Interpretive Structural Modeling

Interpretive Structural Modeling (ISM) is a qualitative-quantitative methodology used to analyze complex systems by identifying and structuring relationships among multiple elements. Rather than relying solely on numerical data, ISM primarily employs expert judgment and logical reasoning to establish causal linkages between factors such as barriers, challenges, or issues. The first step in ISM is to identify the elements (Shashank et al., 2020; Wu et al., 2022). For example, in the development of green ports, common barriers include high investment, poor governing law, or insufficient infrastructure. Experts are then asked to use basic “yes” or “no” assessments to see if one factor has an effect on another by comparing them in pairs. A Structural Self-Interaction Matrix

(SSIM) shows the results of these comparisons by showing all conceivable directional correlations. Then, the SSIM is turned into a binary reachability matrix, where each entry is given a code of “1” (influence exists) or “0” (no influence). Transitivity is utilized to maintain logical coherence; for instance, if barrier A affects B, and B affects C, it is inferred that A impacts C. From this matrix, the reachability set and the antecedent set for each element can be obtained, which allows identification of the hierarchical levels (Kannan et al., 2009; Palit et al., 2022).

Elements at the top of the hierarchy do not drive others, but foundational elements at the bottom do. This leads to a structured hierarchical model, which is sometimes shown as a flowchart, that shows the basic causes and their consequences. ISM helps policymakers and planners figure out what the most important problems are and what actions to take first. It provides an organized way to comprehend interdependencies, which is different from just listing them (Sushil, 2012). This is especially useful when accurate numerical data is not available, since expert judgment is sufficient to build the model. However, ISM alone may sometimes make real-world complexity too simple by limiting replies to only two options. Consequently, researchers frequently combine ISM with fuzzy logic or neutrosophic methodologies, which include ambiguity and partial effect beyond just binary judgments (Diabat & Govindan, 2011; Mathiyazhagan et al., 2013).

2.5 Fuzzy-Matrice d’Impacts Croisés Multiplication Appliquée à un Classement

Fuzzy-MICMAC is an extension of Interpretive Structural Modeling (ISM) that evaluates the driving and dependence power of different elements within a system. MICMAC stands for Matrice d’Impacts Croisés Multiplication Appliquée à un Classement. Fuzzy-MICMAC is different from regular ISM because it lets relationships have different levels of effect. This captures the uncertainty and imprecision that comes with expert judgments (Chen et al., 2022) and makes the analysis more accurate in situations where decisions are hard to determine. The method starts with the reachability matrix from ISM, which is turned into a fuzzy direct influence matrix with the help of experts. Experts use a qualitative scale like low, medium, or high to assess how strongly one aspect affects another. After that, these language concepts are turned into fuzzy numbers, which are usually in the shape of a triangle or a trapezoid. By repeatedly multiplying the fuzzy matrix, it becomes a total impact matrix that shows both direct and indirect effects (Elmsalmi et al., 2021; Mkedder & Das, 2024). Using this matrix, one can figure out how much each element drives others (how much it affects them) and how much it depends on others (how much it is affected by them). After that, elements are put into groupings like autonomous, dependent, linking, or driving factors. This classification helps people who have to make decisions find leverage points, set priorities, and deal with complexity better in situations like green port development.

3. Results and discussion

3.1 Neutrosophic-fuzzy implementation

Table 2 shows the normalized decision matrix derived from expert responses for all fifteen barriers across ten evaluators. Each cell shows a score between 0 and 1 that has been normalized to show how serious or important a barrier is compared to its highest value across all experts. Experts agreed strongly on the importance of Financial Availability (FA) and High Initial Cost (HIC) because they always received higher normalized values. On the other hand, barriers like LMI and OSP had much lower scores, which means they are seen as less important. This matrix backs up the order of importance used in more structural analysis.

The data were analyzed, and the results of neutrosophic fuzzy-based ranking of the 15 identified barriers are listed in **Table 3,** with trends shown in **Figure 1**. Each barrier has been evaluated in terms of T (Truth), the degree to which h experts agree the barrier is influential or significant. I (Indeterminacy) denotes the degree of uncertainty or ambiguity in the expert opinion, while F (Falsity) represents the degree to which a barrier is considered insignificant.

Table 2 Normalized matrix.

Barriers	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10
FA	1	1	0.9	0.9	1	1	0.9	0.8	1	0.9
HIC	0.9	0.8	0.9	1	0.8	0.9	0.9	0.9	0.8	1
RC	0.8	0.9	0.7	0.8	0.9	0.7	0.8	0.9	0.8	0.7
LTC	0.7	0.6	0.8	0.7	0.7	0.6	0.8	0.5	0.6	0.6
TRB	0.6	0.5	0.6	0.7	0.6	0.7	0.5	0.6	0.5	0.5
SCC	0.5	0.4	0.6	0.6	0.5	0.5	0.4	0.5	0.6	0.6
GRD	0.4	0.6	0.5	0.4	0.5	0.4	0.6	0.3	0.5	0.4
SST	0.6	0.5	0.4	0.6	0.4	0.5	0.6	0.5	0.4	0.5
INF	0.5	0.6	0.4	0.5	0.6	0.6	0.4	0.5	0.5	0.6
SAF	0.6	0.5	0.3	0.5	0.5	0.6	0.5	0.5	0.4	0.4
STI	0.3	0.4	0.5	0.4	0.3	0.3	0.4	0.3	0.4	0.4
CPG	0.2	0.3	0.3	0.4	0.2	0.3	0.3	0.4	0.3	0.2
LRA	0.4	0.5	0.4	0.3	0.4	0.3	0.5	0.4	0.4	0.4
LMI	0.3	0.2	0.2	0.3	0.2	0.4	0.3	0.2	0.3	0.2
OSP	0.2	0.3	0.3	0.2	0.2	0.2	0.2	0.3	0.2	0.3

The Score (T - F) is the simple net impact metric that reflects the relative importance or criticality of the barrier; higher scores denote more critical barriers. The following is the analysis based on the results:

3.1.1 Top-ranked barriers:

- FA (Financial Availability): With a T of 0.94 and a very low F of 0.06, this is clearly the most critical barrier. Experts largely agree on its importance with minimal disagreement or uncertainty. This should be the primary focus for intervention.
- HIC (High Initial Cost): Closely following HIC, also highly rated and consistently seen as impactful. This is closely tied to the FA, reinforcing that economic constraints are the dominant challenge.
- RC (Regulatory Complexity): Moderate truth and falsity scores, but high indeterminacy, implying mixed expert views, possibly due to varying port jurisdictions and legal contexts.

3.1.2 Mid-range barriers:

- LTC (Lack of Technical Capacity) and TRB (Technology Readiness Barriers) have moderate T and higher I/F values, indicating more uncertainty and less consensus. These barriers are important but context-dependent; technical limitations may vary widely by region and port size.

3.1.3 Low-impact or downstream barriers:

- Barriers like OSP, LMI, and CPG scored very low. This suggests that either:
  - Experts perceive them as consequences rather than root causes, or
  - These are less pressing or less universal across ports.

3.2 Interpretive structural modeling

To gain deeper insights into the interrelationships among the most influential barriers, Interpretive Structural Modeling (ISM) was carried out using the top seven factors identified through neutrosophic fuzzy evaluation, namely FA, HIC, RC, LTC, TRB, INF, and SCC. This modelling method makes it possible to create a hierarchy that shows how certain obstacles act as driving factors, and others as consequences. Fuzzy-MICMAC analysis was also used to figure out how strong and reliable each barrier was. This helped to separate the root causes from the dependent symptoms. The results provide a strong basis for setting priorities, with a focus on tackling high-impact drivers like FA and HIC to start a chain reaction of improvements across the green port ecosystem.

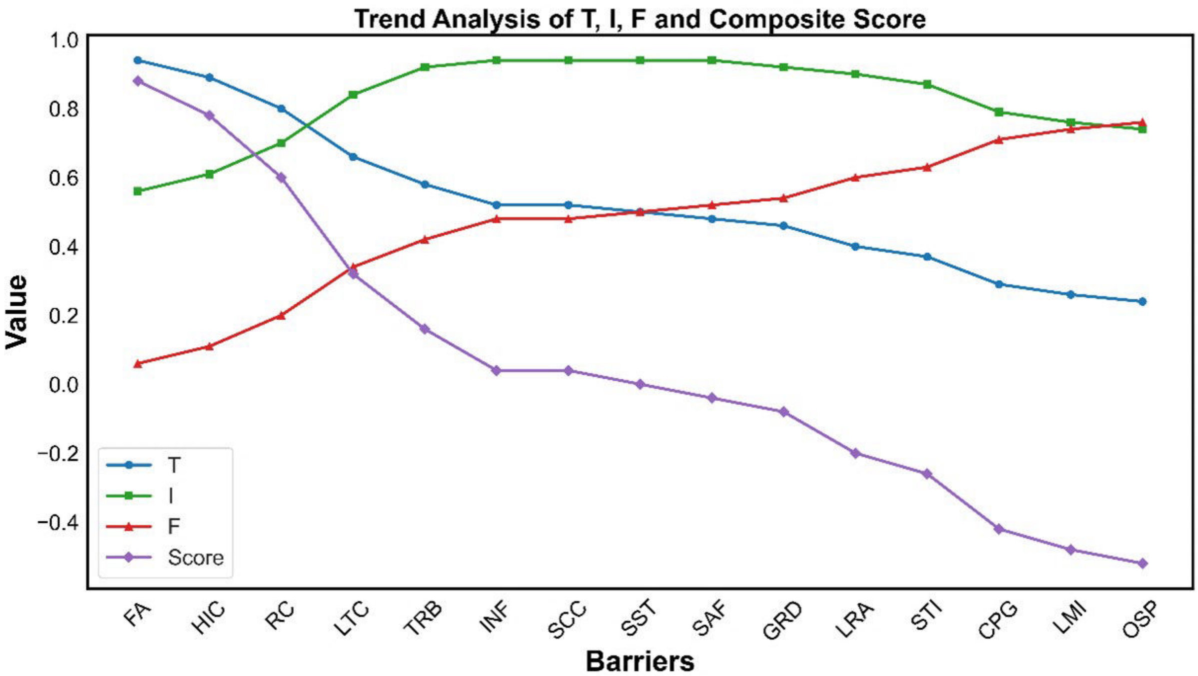


Figure 1 Trends in T, I, F, and composite scores.

Table 3 Ranking of barriers based on neutrosophic-fuzzy score.

Barriers	T	I	F	Score
FA	0.94	0.56	0.06	0.88
HIC	0.89	0.61	0.11	0.78
RC	0.8	0.7	0.2	0.6
LTC	0.66	0.84	0.34	0.32
TRB	0.58	0.92	0.42	0.16
INF	0.52	0.94	0.48	0.04
SCC	0.52	0.94	0.48	0.04
SST	0.5	0.94	0.5	0
SAF	0.48	0.94	0.52	-0.04
GRD	0.46	0.92	0.54	-0.08
LRA	0.4	0.9	0.6	-0.2
STI	0.37	0.87	0.63	-0.26
CPG	0.29	0.79	0.71	-0.42
LMI	0.26	0.76	0.74	-0.48
OSP	0.24	0.74	0.76	-0.52

The Initial Structural Self-Interaction Matrix (SSIM) for the seven selected barriers: FA, HIC, RC, LTC, TRB, INF, and SCC, is shown in **Table 4**. The recommended SSIM shows how the chosen barriers, like FA, HIC, RC, LTC, TRB, INF, and SCC, are related to each other. FA affects HIC, RC, and LTC, which shows the benefit of enough investment in overcoming barriers related to cost and ability. HIC affects RC because following the rules frequently makes things more expensive at first. RC has an impact on LTC, TRB, INF, and SCC. This shows that complicated rules make it harder to coordinate, build, and use technology. LTC affects TRB, which means that not having enough technical skills makes technical resource barriers worse. TRB affects INF, which means that technical problems make the infrastructure less ready. INF has an effect on SCC, which means that infrastructure issues make it harder to coordinate. It is clear that the two directions are affecting each other by marking them with "A."

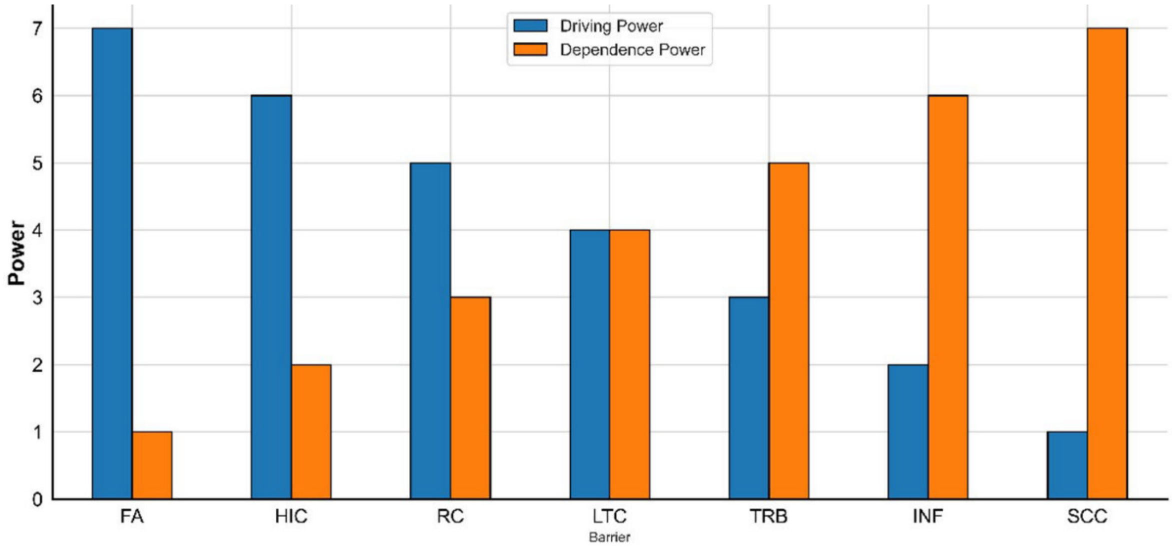
Table 4 Initial structural self-interaction matrix.

	FA	HIC	RC	LTC	TRB	INF	SCC
FA	X	V	V	V	O	O	O
HIC	A	X	V	O	O	O	O
RC	A	A	X	V	V	V	V
LTC	A	O	A	X	V	O	O
TRB	O	O	A	A	X	V	O
INF	O	O	A	O	A	X	V
SCC	O	O	A	O	O	A	X

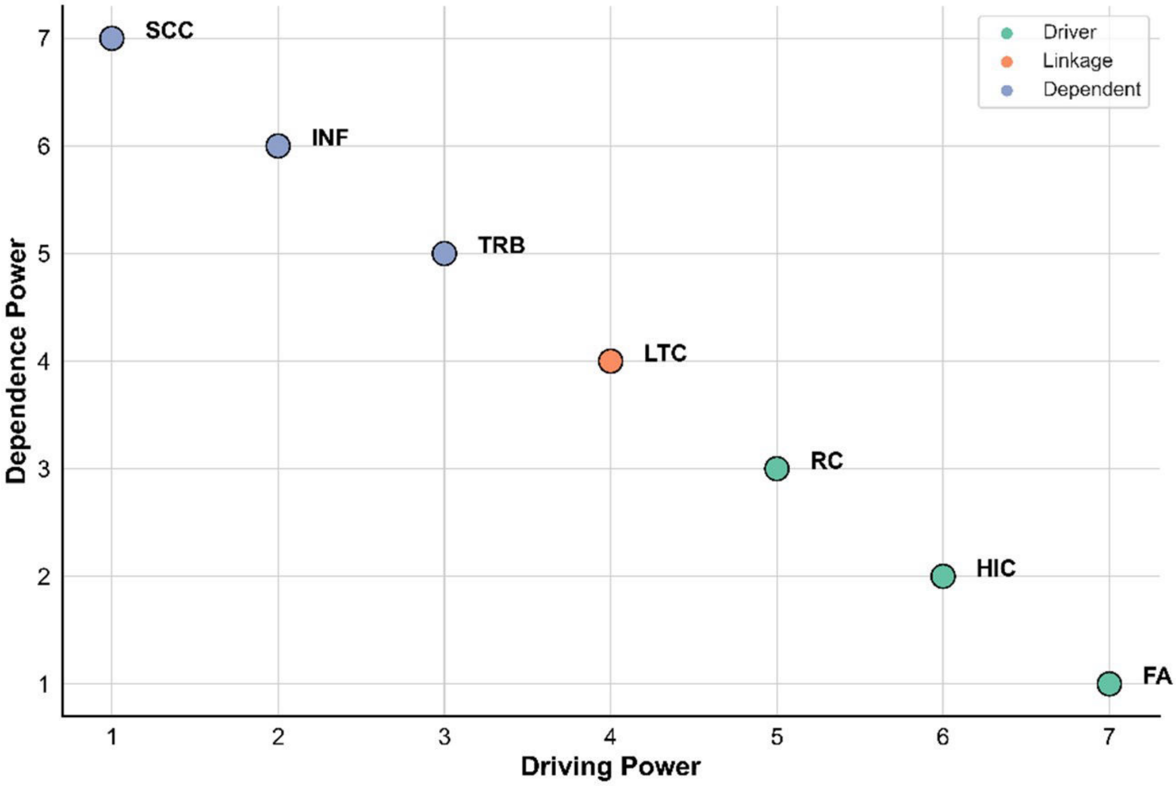
The ISM-based reachability analysis shown in **Table 5** reveals a clear structural hierarchy among the barriers using their interdependencies. FA was the most important strategic node since it connects to all the other nodes in the final matrix. This makes it a key driver of systemic change. RC is also very important since it directly affects LTC, TRB, INF, and SCC, making it a secondary driver. SCC, on the other hand, is the most vulnerable barrier since it has no effect on the outside but can be reached from the inside. This means that it is the result of upstream actions. In the same way, INF and TRB are lower in the hierarchy since they respond to changes made by FA and RC. LTC and HIC act as temporary barriers with modest linkages going both ways. The change from FA to SCC shows a logical flow of influence: financing informs policy (RC), which builds capacity (LTC), pushes implementation (TRB, INF), and lastly affects behavioral or systemic alignment (SCC). This gives intervention planners a clear route to follow.

Table 5 Interpretive Structural Modeling Reachability Matrix.

Initial Reachability Matrix							
	FA	**HIC**	**RC**	**LTC**	**TRB**	**INF**	**SCC**
FA	1	1	1	1	0	0	0
HIC	0	1	1	0	0	0	0
RC	0	0	1	1	1	1	1
LTC	0	0	0	1	1	0	0
TRB	0	0	0	0	1	1	0
INF	0	0	0	0	0	1	1
SCC	0	0	0	0	0	0	1
Final Reachability Matrix							
FA	1	1	1	1	1	1	1
HIC	0	1	1	1	1	1	1
RC	0	0	1	1	1	1	1
LTC	0	0	0	1	1	1	1
TRB	0	0	0	0	1	1	1
INF	0	0	0	0	0	1	1
SCC	0	0	0	0	0	0	1



(a)



(b)

Figure 2 a) Driving vs Dependence of barriers; b) MICMAC classification scatter plot.

Figure 2 illustrates the ISM-based driving-dependence analysis for the identified barriers. **Figure 2a** shows that FA (Funding Availability) has the strongest driving power (7) and the least reliance (1), making it the most important independent barrier. HIC and RC (Regulatory Complexity) come next, with driving strengths of 6 and 5, with lower reliance scores of 2 and 3, respectively. This makes them other important drivers. On the other hand, SCC (Stakeholder Commitment and Collaboration) has a high reliance score of 7 and a low driving power of 1, which means it is a highly dependent outcome. INF (Information Flow) and TRB (Technology Readiness Barriers) are both in the dependent zone, with profiles that are comparable (DR = 2 - 3, DP = 5 - 6). **Figure 2b** shows a graphical cluster-based MICMAC analysis utilizing values for driving and dependency power. Barriers are divided into four groups: FA, HIC, and RC are in the "Driver" category, which shows how important they are for starting system-level reforms. LTC is in the "Linkage" quadrant because it has moderate values (DR = 4, DP = 4) and is both sensitive and influential. In practical terms, small improvements in skills, standard operating procedures, vendor service-level agreements, and spare parts logistics lower the mean time to repair, increase asset availability, and stabilize information flows. This, in turn, strengthens stakeholder commitment and successful standardization. On the other hand, capacity shortages make delays and cost overruns worse, which spreads instability to other nodes that depend on them. The number of qualified technicians per MW, compliance with preventative maintenance, the average lead time for replacement parts, and the mean time to repair (MTTR) will be tracked as quantitative measures of LTC's systemwide impact. On the other hand, INF, TRB, and SCC are in the "Dependent" quadrant, which means that higher-order enablers have an effect on these outcomes. This categorization helps in planning strategic interventions.

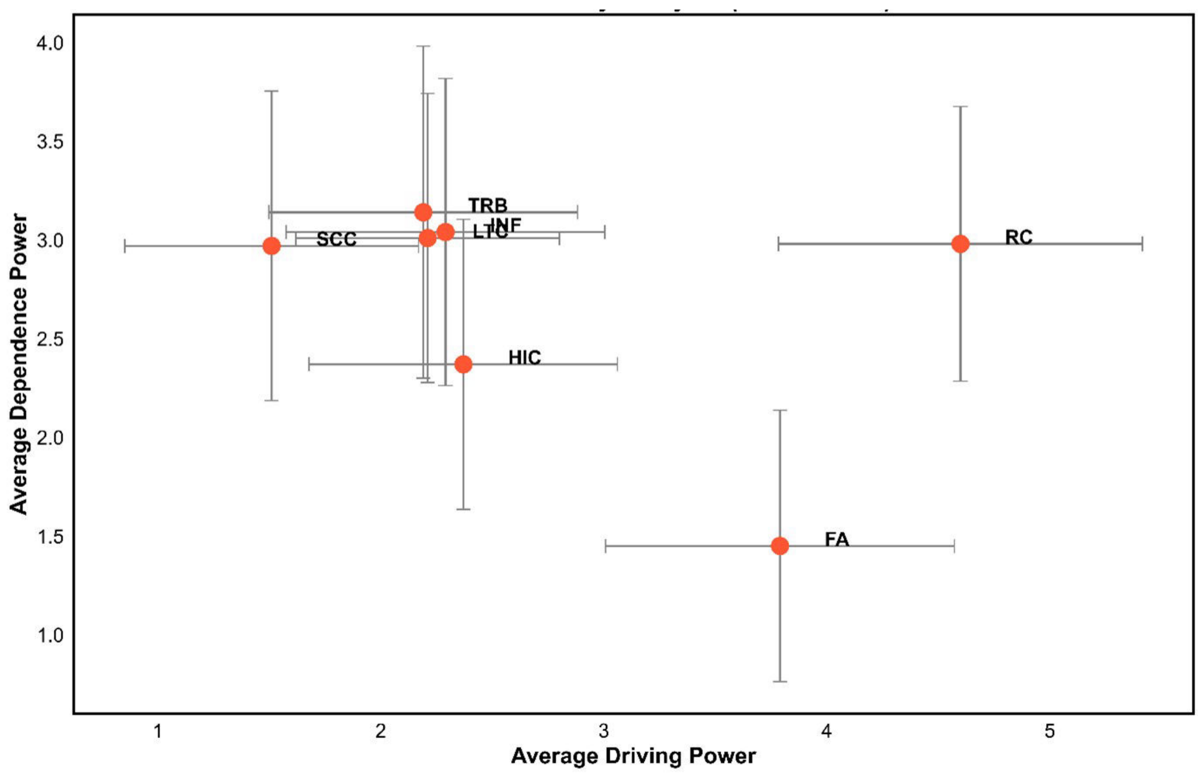
3.3 Monte Carlo-based sensitivity analysis

In this study, Monte Carlo-based sensitivity analysis is employed to assess the robustness and variability of the Interpretive Structural Modeling (ISM) and Fuzzy-MICMAC outcomes under uncertainty. The approach allows for the observation of alterations in the categorization of barriers into drivers, dependents, connections, or autonomous categories when minor modifications are made to the Structural Self-Interaction Matrix (SSIM) throughout several simulation iterations. This probabilistic method gives a better understanding of how stable each barrier's function is, which helps in making better strategic decisions and in creating policies for implementing green ports. The Monte Carlo-based MICMAC sensitivity analysis is depicted in **Figure 3a,** while the Monte Carlo-based distribution of Driving Power across Simulations is illustrated in **Figure 3b**.

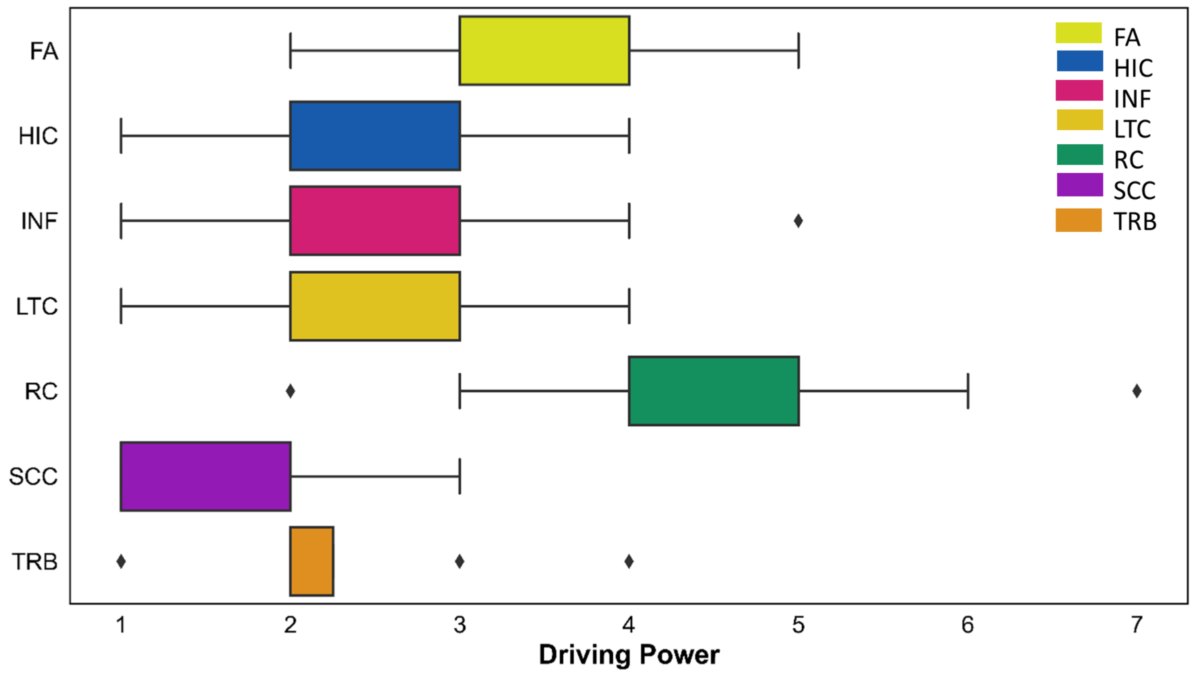
Figure 3 collectively illustrates the outcomes of a Monte Carlo-based MICMAC sensitivity analysis conducted on seven identified barriers: FA, HIC, RC, LTC, TRB, INF, and SCC. **Figure 3a** shows a scatter plot of the average driving power and dependency power of each barrier across 100 simulations, along with their standard deviations. RC (5.0, ~3.0) has the greatest average driving power, making it a crucial driver. SCC (~2.0, ~3.0) and TRB (~2.5, ~3.0), on the other hand, are more reliant, whereas FA (~4.0, ~1.5) has a high driving impact but moderate dependency. INF, LTC, and HIC are all quite close to each other in the center (~2.5 - 3.0 on both axes), which suggests that they would be able to connect when circumstances change. The error bars show how the effect of the barrier changes from one simulation to the next, which shows how strong the structural model is. **Figure 3b** shows a horizontal boxplot that shows the range of driving strengths for each barrier. RC has a large range (around 3 - 7), which shows how dynamic it is. FA, LTC, and HIC have considerable variability, but SCC and TRB have lower medians and narrower interquartile ranges, which means they have less effect. These plots all show that the identified factors are important and consistent, which helps with strategic prioritizing in barrier management.

Figure 4 visualizes the variability and consistency in barrier rankings across 100 Monte Carlo simulations, providing a detailed insight into sensitivity and robustness of the MICMAC analysis. **Figure 4a** shows the rank locations of each barrier, like FA, HIC, INF, LTC, RC, SCC, and TRB, using a heatmap. The color intensity changes from deep red (Rank 1, most crucial) to blue (Rank 7, least critical). RC often shows up in deep red in most simulations, which strengthens its standing as the top driver. FA also always stays toward the top (usually between 1 and 3), but SCC and TRB frequently move toward cooler colors, which means they have less effect. This sequence of shapes shows that FA and RC are always strong barriers. **Figure 4b** shows the same ranking data as a multi-line plot, with the y-axis displaying rankings (1 being the most important) and the x-axis showing the number of simulation runs. RC and FA are always at the top, with RC in first place in most runs. On the other hand, SCC and TRB show chaotic paths, moving back and forth between lower ranks (5 -

7) a lot, which shows that their effect is not consistent over simulations. This variability shows that FA and RC are strong drivers, whereas SCC and TRB are more affected by structural uncertainties in the modelled system.

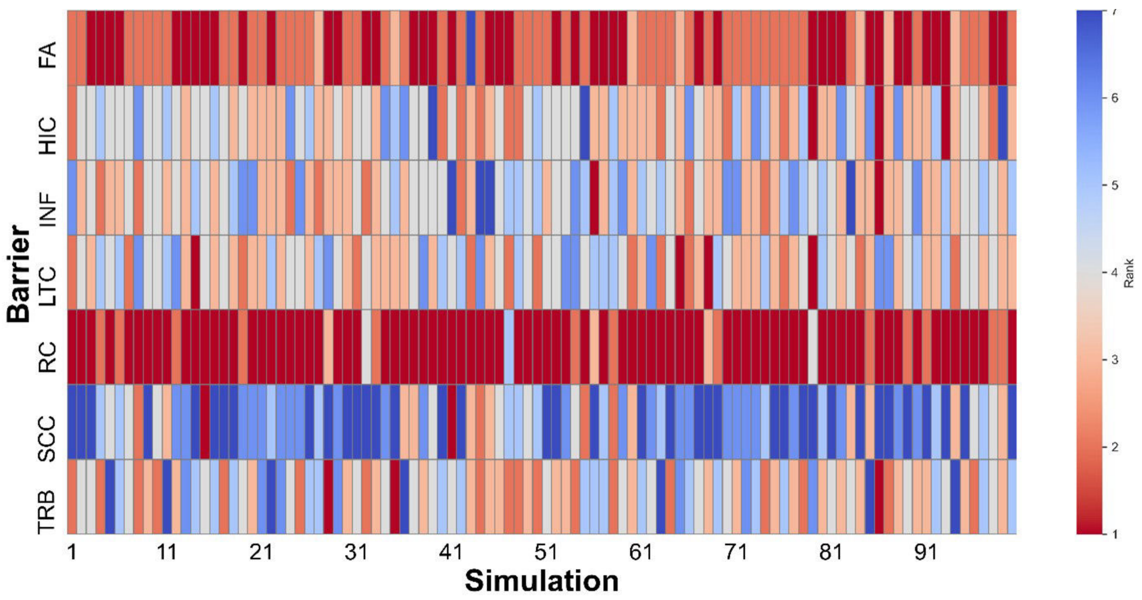


(a)

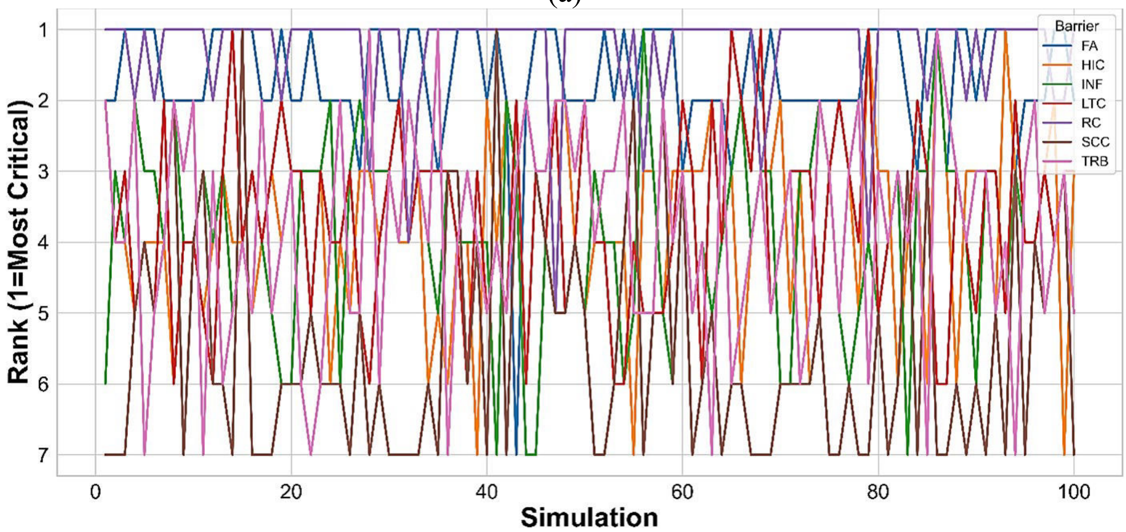


(b)

Figure 3 a) Monte Carlo-based MICMAC sensitivity analysis; b) Monte Carlo-based distribution of Driving Power across Simulations.



(a)



(b)

Figure 4 a) Barrier rank heatmap based on Monte Carlo sensitivity analysis; b) Monte Carlo based rank trajectories of barriers over simulation.

The findings of the present study align with previous research given in **Table 6** and provide a more definitive framework for establishing priorities in uncertain conditions. Financial resources are the primary obstacle. Numerous studies indicate that substantial initial expenditures, inadequate returns relative to inexpensive marine fuels, and stringent financing conditions hinder project initiation. This aligns with the discovery in this paper that financial accessibility and elevated beginning expenses are the primary factors. Reviews and polls indicate that tariff design, absent incentives, and capital burdens need prioritizing of financial instruments and financing avenues. Regulations are another significant obstacle. Previous studies frequently indicate disjointed standards, protracted permitting processes, and varying national regulations. This aligns with the present finding that regulatory complexity is a significant, albeit ambiguous, factor that varies by nation. Comprehensive sustainability research emphasizes the need for effective governance and incentives, corroborating the authors' perspective that robust policy precedes stakeholder engagement. Technical capabilities and grid preparedness are significant, although they are contingent upon the local environment. This aligns with the present discovery that these factors may either enhance or mitigate consequences based on infrastructure and expertise. Surveys identifying operational and standards concerns further indicate that stakeholder commitment and information flow should be regarded as consequences of economic and policy decisions, rather than fundamental causes. The novel aspect here is the integration of neutrosophic-fuzzy ISM with driver-dependence analysis and Monte Carlo simulations. This establishes a definitive and dependable framework of causality and a systematic sequence of actions: prioritize financial and regulatory improvements, followed by skill development and community engagement. This transcends descriptive or single-nation analyses and provides a robust, comprehensive framework for actualizing green ports.

Table 6 Comparison with published literature.

References	Study	Scope and method	Key barriers reported	Notable limitations relative to the present study
Bullock et al. (Bullock et al., 2023)	Accelerating shipping decarbonisation: A case study on UK shore power	Qualitative case study of UK shore power deployment	High upfront costs, weak cost recovery vs. marine fuels, low political salience, coordination gaps	Single-country case; no structured driver-dependence mapping or uncertainty modelling
Kim et al. (Kim et al., 2023)	Key barriers to adopting onshore power supply to reduce port air pollution: Policy implications for the maritime industry in South Korea	Literature review + expert interviews + Fuzzy AHP	Technical standards and awareness	Sector-specific, country-focused; lacks hierarchical causal structure across
Yin et al. (Yin et al., 2020)	Policy implementation barriers and economic analysis of shore power promotion in China	Interviews + cost-benefit models (China)	Regulatory hurdles, tariff/pricing obstacles, capital costs, and grid readiness	Country/market context; limited cross-barrier structural modeling
Wang et al. (Wang et al., 2023)	Identifying industry-related opinions on shore power from a survey in China	Large-scale industry survey	Financial constraints, standardization issues, and operational challenges	Opinion mapping without causal hierarchy or dependence-driving classification
Alamoush et al. (Alamoush et al., 2021)	Revisiting port sustainability as a foundation for the UN SDGs	Critical literature review: governance framework	Governance gaps, incentive design needs, and fragmented actions	Conceptual synthesis: not a barrier, interdependency, or robustness analysis
	Ranking Barriers to Green Port Development: A Neutrosophic-Fuzzy ISM Approach (present study)	Hybrid Neutrosophic-Fuzzy ISM with expert elicitation; MICMAC driver-dependence; Monte Carlo sensitivity	Financial availability and high initial cost as primary drivers; regulatory complexity as an uncertain driver; technical capacity/readiness context-dependent; stakeholder commitment and information flow as dependent	Advances prior work by providing a hierarchical, uncertainty-aware causal map with robustness checks and an explicit prioritization pathway for policy and investment sequencing

4. Conclusions

This study maps the barrier structure for green port implementation using a hybrid neutrosophic-fuzzy ISM approach with expert inputs. Financial availability emerged as the dominant constraint (truth score 0.94), closely coupled with high initial costs, underscoring the primacy of economic barriers. This shows that economic barriers are the most important. Regulatory complexity continues to have a significant and varying influence across nations. In this case, technical capacity and technological readiness are important, whereas stakeholder commitment and information flow act as dependent obstacles. In both driving-dependence and MICMAC assessments, the driver quadrant is always filled with financial availability, high beginning cost, and regulatory complexity. Technical aptitude serves as a linking factor that can either enhance or diminish effects, contingent upon approach. Sensitivity analyses based on Monte Carlo show that the model is stable. Therefore, the first things that policies and managers should focus on are financial and regulatory issues. They should concentrate on upskilling the workforce and getting the community involved to keep the adoption going. The technique makes it clear how things are connected and gives a practical guide for deciding what to do first and how to use resources.

CRediT author statement

Minh Duc Nguyen: Conceptualization; Methodology; Software; Formal analysis; Investigation; Writing - Review & Editing. **Lan Huong Nguyen**: Methodology; Data curation; Resources; Funding acquisition; Writing - Original draft.

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