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Innovative MADM Framework for Strengthening Port Resilience Against Extreme Weather

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ABSTRACT

The increasing frequency and intensity of extreme weather events pose a significant threat to global port infrastructure, disrupting operations, causing economic losses, and compromising the resilience of maritime trade networks. This study aims to address this issue by introducing the Infrastructure Assessment Tool, a decision-making framework based on Multiple Attribute Decision Making methodology, designed to systematically evaluate multiple, often conflicting, criteria in infrastructure assessments. The tool facilitates a comprehensive evaluation of port resilience by considering seven key criteria: structural integrity, road conditions, equipment availability, drainage systems, supporting building conditions, energy systems, and access routes. Data for the tool were collected through a combination of visual inspections, direct measurements, historical record analysis, and expert opinions, which were subsequently converted into a standardized Likert scale for comparative assessment. The Simple Additive Weighting method was utilized to assign relative importance to each criterion, incorporating expert judgment into the evaluation process. The tool's effectiveness was demonstrated through a case study at Tarakan Port, Indonesia. Its flexibility and comprehensiveness enable port managers to proactively assess vulnerabilities, prioritize interventions, and implement targeted measures to strengthen resilience against extreme weather. Consequently, it contributes to ensuring the sustainability and continuous operation of ports, safeguarding their essential role in supporting global trade and economic growth.

1. INTRODUCTION

Ports are vital infrastructure that supports global trade and economic growth. However, they are highly vulnerable to damage and disruptions caused by extreme weather, such as floods, which can lead to significant economic losses. This research aims to develop an assessment tool that can evaluate the resilience of port infrastructure against such threats. Although the importance of assessing port infrastructure has been recognized in various studies, many previous studies tend to focus on technical and structural aspects without considering a holistic approach that encompasses all factors affecting resilience. For example, a study [1] emphasized the importance of structural integrity but did not discuss how drainage systems and equipment availability can affect overall resilience. Furthermore, research [2] showed that despite efforts to enhance resilience, many ports still lack a comprehensive assessment tool to measure their resilience against extreme weather.

This research contributes to filling that gap by developing an assessment tool based on the ASCE Infrastructure Assessment Tool. The tool will consider various factors, including structural integrity, drainage systems, and equipment availability, and involves experts and stakeholders by utilizing diverse data. Thus, this tool will provide guidance to port managers in managing extreme weather risks, enhancing resilience, and ensuring operational sustainability. The tool will be tested at Tarakan Port, Indonesia.

This research not only focuses on tool development but also aims to provide insights on how port infrastructure resilience can be improved through a more comprehensive approach. By integrating expert knowledge and data, this tool offers practical guidance for risk mitigation and resilience enhancement. Its adaptability makes it valuable for enhancing port resilience globally, ensuring sustainable maritime trade. Port infrastructure resilience is a crucial factor in facing various challenges and risks that threaten the continuity of operations and the economic sustainability of a region, especially amid the increasing frequency of extreme weather events. This research focuses on developing an assessment tool to evaluate the resilience of port infrastructure to extreme weather, referring to seven key criteria relevant to port conditions.

1.1 Port quality assessment

Port infrastructure quality assessment is a crucial aspect of sustainable port management and development [3]. Adequate and high-quality port infrastructure plays a vital role in supporting the smooth flow of goods and services, operational efficiency, and the competitiveness of ports at both national and international levels [4]. Therefore, assessing the quality of port infrastructure becomes an urgent need for stakeholders to identify strengths, weaknesses, and potential risks, as well as to formulate targeted improvement and investment strategies [5]. Emphasize the importance of objective and transparent assessments to build a credible reporting system, facilitate effective communication among stakeholders, and track the progress or decline in infrastructure quality over time [6]. Transparency and accountability in port infrastructure quality assessments will enhance public trust in port management, encourage active participation from various parties, and create an environment conducive to port investment and development [7]. A comprehensive and regular assessment of port infrastructure quality can serve as a strong foundation for governments and port operators in planning and implementing such investments [8]. By accurately understanding the condition of port infrastructure, decision-makers can identify investment priorities, allocate resources efficiently, and ensure that every investment has a positive impact on port performance and competitiveness [9]. In addition, port infrastructure quality assessments can also benefit port service users, such as cargo owners, shipping companies, and other businesses [10]. By knowing the quality of port infrastructure, service users can make better decisions regarding port selection, shipping routes, and the types of services needed [11]. This can help improve logistics efficiency, reduce transportation costs, and ultimately have a positive impact on national economic growth. Port infrastructure quality assessments can be conducted using various tools and frameworks developed by international organizations and institutions. These tools, such as Uptime Institute's Tier Standard [12], TIA-942 [13], BICSI 002-2014 [14, 15], ISO/IEC 22237-2 [16], and The Green Grid's Data Center Maturity Model, offer different approaches to assessing aspects such as reliability, design, management, energy efficiency, and interoperability [17]. By utilizing these tools, stakeholders in the port sector can gain a more comprehensive understanding of the condition of port infrastructure, identify areas that need improvement, and develop appropriate strategies to enhance the overall quality and performance of the port [18]. The structural integrity of a port serves as the primary foundation in ensuring its resilience against various threats, particularly natural disasters such as earthquakes, tsunamis, and storms [19]. In research [20], emphasized the importance of considering the stiffness and stability of the structure, reliability against stress and loads, and the extent of damage in assessing the vulnerability of ports to natural disasters. Structural damage to piers, moorings, breakwaters, and quay walls can cause significant operational disruptions, making the assessment of the physical condition of this infrastructure crucial [21]. Previous study [22] also highlights the importance of routine inspections and maintenance to maintain the structural integrity of ports, including monitoring cracks, corrosion, and structural deformation. Proactive maintenance can extend the lifespan of infrastructure and reduce the risk of damage due to excessive loads or harsh environmental conditions.

1.2 Road surface and facility conditions

The condition of road surfaces and facilities is a crucial criterion in assessing the resilience of port infrastructure, particularly against extreme weather events [23]. This criterion focuses on the quality and condition of roads and supporting facilities within and around the port area, such as road surface conditions, road markings, traffic signs, lighting, sidewalks, guardrails, and drainage. Well-maintained road surfaces, clear road markings, and adequate supporting facilities are essential to ensure smooth traffic flow, road user safety, and operational efficiency of the port, especially during extreme weather events such as heavy rain and flooding [24]. Assessing the condition of road surfaces and facilities is important to identify potential risks and problems that can disrupt traffic flow and port operations, especially during extreme weather [25]. By implementing appropriate repairs and maintenance, ports can enhance their infrastructure resilience against various threats and ensure the smooth flow of goods and services [26].

1.3 Availability and condition of equipment

The optimal availability and condition of operational equipment, such as cranes, forklifts, and container handling equipment, are key factors in maintaining the operational efficiency of ports [27]. Previous research [28] found that having sufficient heavy and operational equipment at ports can improve efficiency and decrease ship waiting times. Well-maintained and optimally functioning equipment can minimize the risk of damage and operational disruptions, thereby ensuring smooth flow of goods and reducing operational costs [29]. This research also emphasizes the importance of regular maintenance schedules, including routine inspections, cleaning, lubrication, and replacement of worn components, to ensure optimal equipment performance. Additionally, the availability of sufficient spare parts is also crucial to expedite repairs in case of damage.

1.4 Drainage and water control system

An effective drainage and water control system is essential in preventing flooding and damage to port infrastructure, especially in areas prone to high rainfall or tidal fluctuations [30]. Previous research [31] created a flood risk assessment model for ports that takes into account factors like drainage capacity, channel conditions, and rainfall intensity. This model can assist in identifying flood-prone areas and planning appropriate mitigation measures, such as increasing drainage capacity, constructing embankments, or installing pumps. Furthermore, research [32] examined the impact of climate change on port drainage systems and proposed adaptation strategies to enhance resilience to flooding and waterlogging, such as raising infrastructure elevations and using water-resistant materials. Regular maintenance of drainage channels, cleaning of debris and sediment, and monitoring system performance are also crucial to ensuring the effectiveness of the drainage system [33, 34].

1.5 Condition of supporting buildings

The condition of supporting buildings, such as administrative buildings [35], employee facilities, warehouses, and workshops, also contributes to the overall resilience of the port [36]. These buildings serve as operational control centers, storage areas for goods, and workplaces for port workers. Research [37] shows that poor conditions of supporting buildings can disrupt smooth operations and endanger worker safety. Therefore, it is important to maintain cleanliness, conduct routine maintenance, and ensure these buildings meet relevant safety standards, such as earthquake and fire-resistant building standards [38]. Additionally, the comfort and well-being of employees also need to be considered, as it can affect their productivity and performance.

1.6 Condition of energy and electrical systems

The reliability of energy and electrical systems is a crucial factor in maintaining the continuity of port operations, especially in the era of increasing digitalization and automation [39]. Previous study [40] developed a risk assessment model for port electrical systems, considering factors such as the reliability of electricity supply, the condition of cables and equipment, and fire risks. Disruptions to energy and electrical systems can cause significant economic losses, disrupt port operations, and even endanger worker safety [41]. Therefore, it is essential to ensure the reliability of electricity supply, conduct routine maintenance of electrical equipment, and implement fire prevention measures, such as the use of fire-resistant materials and the installation of fire detection and extinguishing systems.

1.7 Road and access conditions

Well-maintained road and access conditions are essential for the smooth flow of goods and people in ports [42]. Previous study [43] highlight the importance of considering access road conditions, road width, and road surface quality in assessing port resilience to transportation disruptions. Damaged or inadequate roads can hinder the movement of trucks and other vehicles, causing congestion and increasing the risk of accidents [44]. Therefore, regular road maintenance, including repairing potholes and cracks, resurfacing, and drainage cleaning, is crucial. Additionally, it is necessary to consider road widening or the construction of alternative roads to increase capacity and reduce congestion.

2. METHODOLOGY

2.1 Development of infrastructure assessment tool

The Infrastructure Assessment Tool (IAT) was developed as a decision support tool to assess port infrastructure resilience, with a specific focus on ports. This tool is based on the Multiple Attribute Decision Making (MADM) methodology, which allows for the simultaneous evaluation of multiple criteria. This approach aligns with [6], who emphasized the importance of considering various, often conflicting, attributes in infrastructure assessment. The IAT utilizes a Likert scale of 1 to 5 to measure the condition of each infrastructure criterion, where 1 represents 'very poor' and 5 represents 'very good,' consistent with common practice in infrastructure assessment. The development of the IAT is an iterative and comprehensive process, involving several steps. In this study, a Likert scale was used to collect data from stakeholders, including port managers, engineers, and experts, about their perceptions of port infrastructure resilience based on seven established criteria. Each criterion was assessed with relevant statements, and respondents rated their agreement. For example, for the "Structural Integrity" criterion, a statement might be: "How do you assess the rigidity and stability of current port structures?" Respondents would then rate their agreement. Using the Likert scale allowed us to gather quantitative data, identify areas needing improvement, and understand overall perceptions of port resilience.

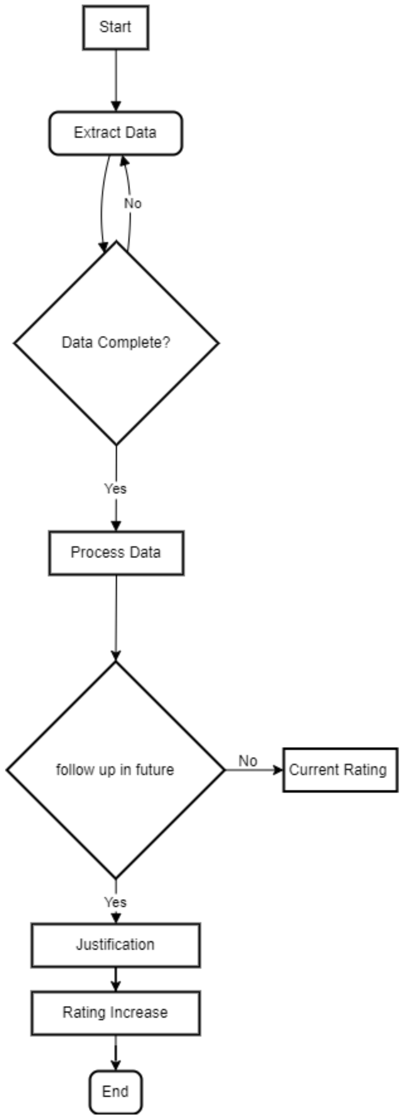

Figure 1. Research flow chart

Figure 1 presents a flowchart of the research process, outlining the key stages from data extraction to final rating. As shown in Figure 1, the process begins with extracting relevant data from various sources. The completeness of the data is then assessed, and if sufficient, the data is processed to determine an initial resilience rating. If the data is incomplete, follow-up actions are initiated to gather additional information.

Criteria Identification i.e., through an extensive literature review, including academic papers, industry reports, and international standards, seven main criteria were identified as crucial in assessing port infrastructure resilience. These criteria encompass key dimensions that contribute to a port's ability to withstand, adapt to, and recover from disruptions. The criteria are as follows:

(1) Structural Integrity: This criterion evaluates the overall condition and stability of critical structural components of the port, such as piers, moorings, breakwaters, and quay walls. It encompasses parameters like the presence and severity of cracks, corrosion, settlement, and other forms of structural damage. Additionally, this criterion also considers the compliance of structural designs with codes and standards, as well as the remaining service life of major structural elements. The assessment of structural integrity is crucial for understanding the port's vulnerability to natural hazards like earthquakes and tsunamis.

(2) Road Surface and Facility Conditions: This criterion evaluates roads and facilities in and around the port. Well-maintained roads, clear markings, and adequate facilities ensure traffic flow, safety, and efficiency, especially during extreme weather. Damaged roads hinder cargo transport, cause accidents, and worsen flooding. Thus, road maintenance is key to enhancing port resilience.

(3) Availability and Condition of Equipment: This criterion assesses the availability, functionality, and maintenance status of essential equipment required for efficient port operations. This includes cranes, forklifts, container handling equipment, navigation aids, and other machinery. Parameters considered include the age and condition of equipment, frequency of breakdowns, maintenance schedules, and availability of spare parts. A well-maintained and fully functional equipment inventory is crucial to ensure smooth port operations and minimize downtime in case of disruptions.

(4) Drainage and Water Control Systems: Effective drainage and water control systems are essential for preventing flooding and ensuring the safe movement of goods and people within the port area. This criterion evaluates the design and performance of the port's drainage infrastructure, including the capacity of drainage channels, the presence of pumping stations, and the effectiveness of flood control measures. It also considers the maintenance status of these systems and their ability to handle extreme rainfall events.

(5) Condition of Supporting Buildings: This criterion assesses the condition of buildings that are essential for supporting port operations, such as administrative offices, warehouses, workshops, and control towers. The assessment includes evaluating the structural integrity of these buildings, their functionality, and the adequacy of maintenance and repair efforts. Well-maintained and functional supporting buildings are crucial to ensure the smooth flow of information, coordination of activities, and overall operational efficiency of the port.

(6) Condition of Energy and Electrical Systems: Reliable energy and electrical systems are essential to support port operations, lighting, communication, and safety systems. This criterion evaluates the condition and reliability of the port's electrical infrastructure, including power generation and distribution systems, transformers, switchgear, and lighting. This criterion also considers the safety of electrical installations and compliance with relevant electrical codes and standards.

(7) Road and Access Conditions: The condition of roads and access points leading to and within the port area significantly impacts the efficiency of cargo movement and overall port accessibility. This criterion assesses the quality of road surfaces, the presence of adequate signage, and the capacity of access routes to accommodate traffic volume. It also considers the maintenance of these roads and their ability to withstand heavy loads and adverse weather conditions.

The selection of seven criteria for port resilience was based on a comprehensive analysis of literature and best practices in infrastructure management. These criteria were chosen for their relevance, as they reflect essential dimensions like structural integrity and drainage systems, which are crucial during extreme weather. They are comprehensive, covering both physical and managerial aspects, practical, as they can be effectively measured and evaluated, and flexible, allowing for adaptation to different port conditions. This rationale helps in understanding how Technical Analysis Innovations can enhance port infrastructure resilience.

Parameter Definition: For each of the seven criteria, specific parameters are defined to provide a measurable basis for evaluating their performance [45]. These parameters are carefully selected to capture the most relevant aspects of each criterion's contribution to port resilience. For instance, under the "Structural Integrity" criterion, parameters such as the presence and severity of cracks, corrosion, and settlement are included. Similarly, for the "Availability and Condition of Equipment" criterion, parameters such as equipment age, frequency of breakdowns, and maintenance schedules are considered.

Data collection involved multiple methods. Visual inspections assessed infrastructure condition. Direct measurements quantified parameters like road width and drainage capacity. Historical data analysis revealed past performance and vulnerabilities. Surveys and interviews gathered qualitative insights and expert opinions from port personnel.

Data Conversion to Likert Scale: The collected data is systematically converted into Likert scale scores (1-5) for each parameter. To ensure consistency and objectivity in the assessment process, detailed guidelines are developed, outlining specific criteria for assigning each Likert score. This involves determining thresholds and benchmarks for each parameter based on industry standards, best practices, and expert judgment. Converting the data into Likert scores facilitates a standardized and comparable assessment of port infrastructure across various criteria.

Each criterion's impact on port resilience varies. The Simple Additive Weighting (SAW) method was used to prioritize these criteria. Experts assessed the relative importance of each criterion. These comparisons were combined to create weights reflecting expert judgment. SAW calculates a total score for each alternative based on these weights and performance values.

2.2 Case study: Tarakan Port

Tarakan Port, located in North Kalimantan, Indonesia, was chosen as a case study to validate and demonstrate the practical application of the IAT. This port plays a crucial role in facilitating trade and transportation in the northern border region of Indonesia and Malaysia, making its resilience paramount. The port's vulnerability to natural disasters, such as floods, earthquakes, and tsunamis, further emphasizes the need for a comprehensive resilience assessment.

The implementation of the IAT at Tarakan Port involved a systematic process. Data collection was conducted for each parameter identified within the IAT framework [46]. This data was then converted into Likert scores using established guidelines, and weighted scores were calculated for each criterion based on the weights obtained from SAW. By aggregating the weighted scores, an overall resilience score was determined for Tarakan Port.

This case study not only serves to validate the IAT as a practical tool for assessing port resilience but also provides valuable insights into the specific strengths and weaknesses of the port infrastructure. The findings from this assessment can be used to inform decision-making processes regarding infrastructure investment, maintenance strategies, and risk mitigation measures, ultimately enhancing the port's resilience to future challenges.

3. RESULT

The assessment was conducted using a case study of the port in Tarakan City by obtaining data, which was then analyzed using the Infrastructure Assessment Tool (IAT). Seven predetermined criteria with parameters were calculated based on established provisions. The following is an assessment based on the existing conditions.

The analysis of port infrastructure using the IAT in Table 1 yielded a total weighted (score of 0.72), indicating a significant need for improvement. Although the aspect of structural integrity shows relatively good performance (score of 0.79), the presence of structural damage (score of 0.63) requires urgent attention to prevent potential safety and operational risks. The condition of roads and supporting facilities, including road markings (score of 0.67) and access to the port (score of 0.76), shows below-average scores and requires enhancements to ensure operational efficiency and safety. The drainage system also needs attention (score of 0.70), considering the potential negative impact of waterlogging on port activities. Improvements in these areas, particularly in road repairs, road markings, port access, and handling structural damage, are necessary to enhance overall operational performance and safety. Conversely, the energy and electrical systems show satisfactory conditions (score of 0.81).

Table 1. Assessment analysis of Tarakan Port infrastructure using the IAT

Criteria	Parameter	Basic Scores	Standardized Scores	Weights	Weighted Totals
Structural Integrity	Rigidity and Stability	3.97	0.79	0.05	0.08
	Structural Reliability Against Stress and Loads	4.10	0.82	0.05	0.08
	Structural Damage	3.14	0.63	0.09*	0.06
Road Surface and Facility Conditions	Surface Roughness and Wear	3.28	0.66	0.04	0.03
	Condition of Road Markings and Signage	3.34	0.67	0.09*	0.03
	Condition of Supporting Facilities	3.52	0.70	0.09*	0.03
Availability and Condition of Equipment	Availability of Heavy Equipment and Operational Equipment	3.76	0.75	0.05	0.04
	Condition of Machinery and Equipment	3.66	0.73	0.05	0.04
Drainage and Water Control System	Effectiveness of the Drainage System	3.52	0.70	0.05	0.08
	Condition of Drainage Channels and Water Control	3.55	0.71	0.05	0.08
Condition of Supporting Buildings	Condition of Administrative Buildings and Employee Facilities	3.55	0.71	0.09*	0.03
	Cleanliness and Maintenance of Support Buildings	3.38	0.68	0.09*	0.03
Condition of Energy and Electrical Systems	Availability and Reliability of Electricity Supply	4.03	0.81	0.05	0.04
	Condition of Cables, Electrical Equipment, and Installations	3.48	0.70	0.05	0.03
Road and Access Conditions	Condition of Access Roads to the Port	3.79	0.76	0.10*	0.04
	TOTAL			1.00	0.72

*Changes to the weights are made after the interviews have been conducted to prioritize categories in order to improve the grading scheme.

Table 2. Grading scheme

Grading Scheme			
A	=	90-100%	Exceptional
B	=	80-89%	Good
C	=	70-79%	Mediocre
D	=	51-69%	Poor
E	=	50% or lower	Inadequate

Based on Table 2, the score of 0.72 obtained from the IAT is categorized as **Mediocre (C)**. Although some infrastructure components, such as structural integrity, show relatively good performance, the overall score indicates a significant need for improvement in various areas. Scores below 80% highlight weaknesses that need to be addressed to enhance port operational efficiency and safety. Focused improvements in areas with low scores, such as structural damage, road conditions, and drainage systems, are crucial to elevate the overall port infrastructure rating and achieve higher standards. Further analysis is required to identify the causes of low scores and formulate effective and measurable improvement strategies.

This research findings [47] revealed that the quality of port infrastructure has a significant positive impact on the national economy, and previous research [48] emphasized in their research the importance of making informed decisions based on information regarding infrastructure upgrades and forecast development to achieve port resilience.

4. DISCUSSION

The observed improvement from a 'Poor' to a 'Mediocre' rating underscores the positive impact of recent efforts to enhance port resilience. However, the current score highlights the need for continued focus and targeted interventions to achieve a 'Good' or even 'Exceptional' level of preparedness. The following discussion delves deeper into the assessment results, providing insights into the strengths and weaknesses across various criteria, and offering recommendations for further improvement.

The assessment of the port infrastructure, as detailed in Table 3, reveals several critical criteria that contribute to its overall resilience and functionality. Structural integrity is rated highly, indicating that the port can withstand pressures from environmental factors and operational activities without sustaining damage to its pilings or slabs. The road surface and facility conditions are also deemed satisfactory, ensuring safe and efficient access for vehicles and personnel. Furthermore, the availability and condition of equipment are assessed as adequate, which is essential for maintaining operational performance. The drainage and water control systems are functioning effectively, preventing flooding and ensuring the proper management of water flow. Additionally, the condition of supporting buildings is satisfactory, as they provide necessary shelter and support for port operations. The energy and electrical systems are evaluated as reliable, ensuring continuous power supply, while the road and access conditions are considered good, facilitating smooth movement of goods and people to and from the port. In summary, these evaluations highlight the port's readiness to manage extreme weather conditions while ensuring continuous operations.

Table 3. Justification of scores

Assessment Criteria	Justification of Scores
Structural Integrity	• 79% - The structure of the port's pier is assessed as strong and stable because there is no damage to the piles or plates. • 82% - The pier is assessed as good because it is reliable in withstanding pressure from berthed ships, including horizontal forces due to wind and currents, as well as vertical forces due to ship weight and cargo. • 63% - The port's pier has cracks in its concrete structure, but it is assessed as adequate because it is deemed not to reduce its functionality and there is regular maintenance.
Road Surface and Facility Conditions	• 66% - The main access road to the port typically experiences very heavy traffic from container trucks and other vehicles. This causes significant wear and tear on the road surface, especially in areas with curves and intersections. • 67% - Road markings and signs have been placed in strategic and easily visible positions for drivers, however, some materials on the signs are unclear due to corrosion. • 70% - Proper lighting can increase visibility, reduce the risk of accidents, and create a safe environment.
Availability and Condition of Equipment	• 75% - The heavy equipment is adequate and functional to support port operations. • 73% - The condition of machinery and equipment at the port, as a key factor in determining overall performance, safety, and reliability, is still able to support port activities well.
Drainage and Water Control System	• 70% - The drainage system's capacity to drain a certain amount of water within a specific time frame is still good. However, the flow rate is not yet optimal, resulting in sedimentation and clogging of the drainage channels due to shoaling. • 71% - The water control structures are functioning well and are capable of protecting the port from flooding. The quality of water discharged from the drainage system meets environmental standards.
Condition of Supporting Buildings	• 71% - The condition of administrative buildings and employee facilities at the port refers to the physical state, functionality, and suitability of the buildings and facilities used for administrative activities and to support the well-being of employees within the port environment, which are in good condition. • 68% - Efforts to maintain and preserve the physical condition of buildings that are not directly involved in the cargo handling process, but still play an important role in supporting port operations.
Condition of Energy and Electrical Systems	• 81% - Electricity is always available without interruption. However, in practice, there is always the possibility of blackouts or disruptions. Port electricity typically has a backup system, such as a diesel generator, to ensure continuity of power supply. • 70% - The good condition of cables, electrical equipment, and electrical installations is essential to ensure safety, efficiency, and operational reliability, all of which directly impact the smooth flow of logistics and transportation activities at the port.
Road and Access Conditions	• 76% - The condition of this access road is assessed as good because it has a direct impact on the smooth flow of goods and people to and from the port.

Table 4. Justification of weights

Assessment Criteria	Justification of Weights
Structural Integrity	• 5% - The rigidity and stability of port structures are crucial for safety and resilience against operational loads and environmental conditions. • 5% - Structural reliability ensures that port facilities can withstand various stresses and loads without experiencing significant damage or failure. • 9% - Structural damage to port facilities can have a significant impact on safety, operations, and repair costs. Therefore, this criterion is given a high weight to emphasize the importance of proactive damage prevention and management.
Road Surface and Facility Conditions	• 4% - Although important, this criterion is given a lower weight compared to other criteria because its impact on port operations is relatively smaller. Rough or worn road surfaces can be repaired at a relatively lower cost compared to structural damage or problems with supporting facilities. • 9% - Clear Road markings and signage are crucial for safety and traffic efficiency in the port. The high weight reflects their crucial role in preventing accidents and ensuring the smooth flow of goods. • 9% - Supporting facilities such as warehouses, workshops, and security offices are essential to support port operations. Poor conditions can disrupt smooth operations and decrease productivity.

Availability and Condition of Equipment	• 5% - The availability of adequate heavy equipment and operational equipment is crucial to support the smooth flow of loading and unloading activities and overall port operations. • 5% - Good condition of machinery and equipment will improve the efficiency, reliability, and safety of port operations.
Drainage and Water Control System	• 5% - An effective drainage system will prevent waterlogging and flooding, protect port infrastructure, and maintain the environment. • 5% - Good condition of drainage channels and water control will ensure that the drainage system functions optimally and effectively in managing water at the port.
Condition of Supporting Buildings	• 9% - Good condition of administrative buildings and employee facilities will improve employee performance and well-being, which ultimately has a positive impact on the overall performance of the port. • 9% - Good cleanliness and maintenance of support buildings will create a healthy and safe work environment, as well as extend the lifespan of the buildings.
Condition of Energy and Electrical Systems	• 5% - A reliable and stable electricity supply is crucial to support all port operations, including loading and unloading, transportation, and communication systems. • 5% - The good condition of cables, electrical equipment, and installations will ensure the safety and reliability of the electricity supply at the port.
Road and Access Conditions	• 10% - Good access roads are crucial for the smooth flow of goods and people to and from the port. Poor road conditions can cause congestion, accidents, and vehicle damage, impacting logistics efficiency and costs.

Table 4 meticulously delineates the relative importance of various assessment criteria in evaluating the port's resilience and functionality. Structural integrity is accorded significant weight due to its critical role in enduring both operational demands and environmental impacts. The conditions of road surfaces and facilities are appropriately weighted, emphasizing their importance in mitigating accidents and ensuring seamless traffic operations. The availability and condition of equipment, essential for operational efficacy, justify their substantial weighting. Effective drainage and water control systems, indispensable for preventing flooding and infrastructure damage, are thus duly weighted. The condition of supporting buildings, which is vital for maintaining a safe and productive working environment, is also considered. Furthermore, the reliability of energy and electrical systems, ensuring uninterrupted operations, and the quality of road and access conditions, facilitating efficient logistics, are assigned appropriate weights. Collectively, these weighted criteria underscore a comprehensive approach to enhancing and assessing port resilience.

An in-depth analysis of the seven criteria and assessment parameters within the port infrastructure assessment tool revealed that weight adjustments were made based on field observations and in-depth discussions with experts and academics. These adjustments aimed to refine the assessment of port infrastructure resilience to extreme weather, not only in terms of physical conditions but also considering its impact on the overall operation, safety, and sustainability of the port. The "Structural Integrity" criterion, particularly the "Structural Damage" parameter, received a significant weight increase from 0.04 to 0.09. This reflects the central role of piers in port activities, where structural damage can directly disrupt operations and pose serious safety risks, especially during extreme weather. This weight increase ensures that repair and maintenance efforts are focused on the most critical elements for the port's survival in the face of extrametrical weather [49]. In the "Road Surface and Facility Conditions" criterion, two parameters also experienced weight increases. "Road Markings or Directional Signs Condition" and "Supporting Facilities Condition" were each raised from 0.04 to 0.09 and from 0.05 to 0.09, respectively. This indicates that safety and smooth traffic flow within the port, especially during bad weather, are considered as important as the physical condition of the road itself [50]. Adequate supporting facilities, such as clear signage and sufficient lighting, play a crucial role in preventing accidents and ensuring the port's operational efficiency even during extreme weather [50]. Furthermore, the "Condition of Supporting Buildings" criterion also saw an increase in the weight of two of its parameters. Both "Condition of Administrative Buildings and Employee Facilities" and "Cleanliness and Maintenance of Supporting Buildings" were raised from 0.05 to 0.09. This decision emphasizes that the condition of supporting buildings not only affects the comfort and productivity of port employees but can also impact the overall quality of service and operational efficiency, especially when facing extreme weather conditions [51]. Finally, the weight of the "Road and Access Conditions" parameter was increased from 0.05 to 0.10. This increase highlights that port accessibility is a key factor in maintaining the smooth flow of logistics and connectivity with the surrounding area, especially during extreme weather events that can disrupt access. Well-maintained roads and access will ensure the smooth transportation of goods and people, as well as reduce the risk of delays and operational disruptions due to poor road conditions during extreme weather [52]. With these weight adjustments, the assessment tool becomes a more comprehensive and accurate instrument for evaluating the resilience of port infrastructure against extreme weather [53]. The results of the assessment tool not only provide an overview of the physical condition of the infrastructure but also offer more targeted recommendations for repairs and improvements, considering their impact on various aspects of port operations in the face of extreme weather. Thus, the assessment tool can be an effective decision support tool for port managers in enhancing the overall resilience and sustainability of the port in facing the challenges of extreme weather.

Despite its effectiveness in evaluating port resilience, the IAT has limitations and potential errors. Visual inspections can be subjective, influenced by inspectors' perceptions and weather conditions. Physical measurements may suffer from inaccuracies due to measurement errors or inconsistent techniques. Likert scale data collection can introduce respondent bias, with answers skewed by personal experiences or a desire to provide "correct" answers. The assessment might not cover all infrastructure aspects, leading to unrepresentative results if only a small fraction is evaluated. Limited stakeholder involvement can reduce result validity. Environmental factors like weather and geography also affect resilience, necessitating periodic assessments. Recognizing these challenges allows for refining the IAT methodology, ensuring more accurate and reliable infrastructure evaluations. This discussion highlights current results and offers insights for improving future assessments, focusing on more objective and comprehensive data collection to minimize bias.

5. CONCLUSIONS

The increase in score from 52% (category "D" or "poor") to 72% indicates that improvement efforts have been made. However, there is still room for further improvement for the port to achieve a higher level of resilience (category "B" or "good", or even "A" or "exceptional"). Some recommendations for improvement based on the IAT analysis results include:

1) Structural Integrity: Repairing cracks in the concrete pier structure and addressing corrosion in some areas are necessary to enhance the robustness and stability of the structure.

2) Road Surface and Facility Conditions: Repairing worn road surfaces, replacing or repairing damaged road markings, and improving supporting facilities such as road lighting will enhance safety and traffic efficiency at the port.

3) Drainage and Water Control System: Optimizing flow velocity and managing sedimentation in drainage channels will improve the effectiveness of the drainage system in preventing flooding.

4) Condition of Supporting Buildings: Regular maintenance and improved cleanliness of supporting buildings will create a better working environment and support smooth port operations.

5) Condition of Energy and Electrical Systems: Routine inspections and maintenance of cables, electrical equipment, and installations will ensure the reliability of the electricity supply at the port.

This study developed the Infrastructure Assessment Tool (IAT) to evaluate the resilience of Tarakan Port against extreme weather. Results indicate that while certain infrastructure aspects, such as structural integrity, performed well, areas like drainage systems and emergency preparedness need further attention.

The study has limitations, such as assumptions about stable weather, biased data collection methods, and limited sample coverage. Periodic assessments are necessary for a more accurate picture. The study offers valuable insights for port managers in devising effective risk mitigation strategies. Further research on drainage systems and emergency preparedness at Tarakan Port is recommended. Developing more accurate data collection methods and comparative studies with other ports can enhance infrastructure resilience and risk mitigation strategies.

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