



Creating a Systemic Risk Assessment Framework for Seaport Ecosystem

About this document

This document, ‘Creating a Systemic Risk Assessment Framework for Seaport Ecosystems’, provides a comprehensive analysis of systemic risk management in port ecosystems, focusing on the Paradip Port Authority and Visakhapatnam Port Authority as pilot case studies. By applying the integrated disaster resilience framework and systemic risk assessment methodology, the study identifies key vulnerabilities and proposes strategic recommendations. Emphasizing a holistic approach, it highlights the importance of strengthening resilience across critical infrastructure and interconnected systems to enhance the sustainability and security of seaports.

Potential user

Policymakers, disaster management practitioners, researchers, and infrastructure planners will find this document valuable for strengthening systemic risk resilience. It is also useful for stakeholders involved in governance, cross-sector collaboration, and climate adaptation initiatives.

The Team

Advisory Team

Vice Admiral Pradeep Chauhan	Professor Rajib Shaw	Mr Amit Prothi
		Mr Ramraj Narasimhan

Research Team

Dr Chime Youdon	Dr Arunabh Mitra	Mr Kiran Gowda
Dr Gulshan Sharma		Ms Vinshi Raj

Published by

National Maritime Foundation (NMF), India
India Japan Laboratory, Keio University, Japan
Coalition for Disaster Resilient Infrastructure (CDRI)

November 2026



The contents of this publication may be copied, distributed, and displayed alike and with attribution only for non-commercial purposes.

Please refer to this publication as follows:

Youdon, C., Mitra A., Shaw R., Gowda, K., Raj V., Sharma, G. (2026): Creating a Systemic Risk Framework for Seaport Ecosystem, Published by National Maritime Foundation, India and India Japan Lab, Keio University, Japan, and CDRI.

Acknowledgement

The authors sincerely thank the Coalition for Disaster Resilient Infrastructure (CDRI) for its support and commitment to this collaborative project. We are especially thankful to Vice Admiral Pradeep Chauhan, Director-General of the National Maritime Foundation (NMF), Professor Rajib Shaw of Keio University, and Mr Amit Prothi, Director-General, CDRI for their unwavering guidance and invaluable academic insights throughout the course of this research.

We extend our deep appreciation to Vice Admiral Sameer Saxena, Chief of Staff, Eastern Naval Command; Shri P.L. Haranadh, Chairman of the Paradip Port Authority; and Dr Madhaiyaan Angamuthu, Chairman of the Visakhapatnam Port Authority, for facilitating the field visit, which played a crucial role in advancing our research and achieving our objectives.

Special recognition is due to NMF research interns—Mr Chime Rigzin, Ms Shakshi Shree, and Ms Shardha—for their contributions to data collection. We also extend our gratitude to Ms Ayushi Srivastava, Naval naval architect, for her valuable assistance in stakeholder identification.



Assessment of Systemic Risk in the Seaport Ecosystem:

A Case Study of the Paradip Port Authority and Visakhapatnam Port Authority

Abstract

Seaports are vital conduits for global trade, handling 80 percent of the world's trade volume. They are essential gateways to international markets and supply chains, playing a pivotal role in fostering global development. However, despite their significance, seaports are susceptible to significant operational disruptions caused by extreme weather events, resulting in substantial downtime and extensive physical damage. The intricate dependencies within specific supply chains routed through ports create a complex network where disruptions can manifest in unexpected ways, triggering both primary and cascading effects. This complexity is further compounded by the key role seaports play in maritime transport and coastal economic activities. While there is a growing acknowledgement of the need for a holistic approach to risk management, existing frameworks often lack a clear pathway to operationalizing systemic risk. This study aims to address this gap by examining the potential impact of systemic risks, focusing on cyclones and flooding, on the operations and functions of Indian seaports. The case studies of the Visakhapatnam Port Authority (VPA) and the Paradip Port Authority (PPA) are particularly instructive. Both ports, strategically located along open coastlines or in low-lying areas and deltas, are exposed to a range of hazards, including storm surges, high winds, flooding, tsunamis, and rising sea levels. To gain a comprehensive understanding of how these ports would be affected, a 'Systemic Risk Assessment (SRA) Framework' has been created. This framework is applied to the VPA and PPA through a field study to evaluate their current vulnerability and resilience levels in the face of climate change. The research findings are analysed systemically, taking each aspect of the systems into account. Additionally, the study discusses global best practices for seaport adaptation measures and strategies aimed at enhancing the resilience of Indian seaports.

Keywords: Resilience, Seaport Ecosystem, Systemic Risk, Cyclones, Flooding, Climate Change, Paradip Port, Visakhapatnam Port, Systemic Risk Capability Assessment

Contents

Introduction	04
Methodology	10
Building of Systemic Risk Assessment Framework for Seaports in India	
Analysis	12
Outcome of the Systemic Risk Assessment Survey	34
Way Ahead	37
Global Best Practices	39
Conclusion	42

List of Figures

Figure 1	Landscape of seaport ecosystem	6
Figure 2	Quasi-quantitative framework for operationalizing systemic risk assessment for seaports	10
Figure 3	Framework for systemic risk assessment for seaports	11
Figure 4	Schema for systemic risk capability assessment survey domains, systems, and temporal scales	11
Figure 5	Key impacts within the components of the seaport ecosystem	20
Figure 6	Systemic risk capability assessment score between Paradip Port Authority and Visakhapatnam Port Authority as of 2023, 2030, 2050	28
Figure 7	Domain-wise inter- and intra-system scores for the Visakhapatnam Port Authority and Paradip Port Authority for 2023, 2030, 2050	29
Figure 8	Domain-wise break up of inter-system score for the Visakhapatnam Port Authority and Paradip Port Authority for 2023, 2030, and 2050	29
Figure 9	System-wise scores for Paradip Port Authority and Visakhapatnam Port Authority	33
Figure 10	Physical and infrastructure systems analysis in the Visakhapatnam Port Authority and Paradip Port Authority	33
Figure 11	Economic and financial systems analysis in the Visakhapatnam Port Authority and Paradip Port Authority	34
Figure 12	Ecological and environmental systems analysis in the Visakhapatnam Port Authority and Paradip Port Authority	34
Figure 13	Human, social, and cultural system analysis in the Visakhapatnam Port Authority and Paradip Port Authority	34
Figure 14	Political and governance system analysis in the Visakhapatnam Port Authority and Paradip Port Authority	35

List of Tables

Table 1	Key systems identified in the seaport ecosystems	13
Table 2	Key components identified within the five identified systems in the seaport ecosystem	13
Table 3	Key stakeholders within the components of the seaport ecosystem	19
Table 4	Key assets within the components of the seaport ecosystem within Visakhapatnam Port Authority and Paradip Port Authority Ports	19
Table 5	Central nodes in the seaport ecosystem, their significance, and connections	22
Table 6	Critical for resilience ratings by components in the seaport ecosystem	23
Table 7	Inter-component relationship by component in the seaport ecosystem	24
Table 8	System breakdown risk rating for seaport ecosystem components	25
Table 9	Key insights from an institutional design perspective (inter)	29
Table 10	Key insights from an institutional capacity perspective (inter)	30
Table 11	Key takeaways from a governance perspective (inter)	31
Table 12	Key takeaways from system understanding perspective (inter)	32



Photos of the team during a field visit to Visakhapatnam Port Authority and Paradip Port Authority and fishing harbours



Introduction

Maritime transport plays a vital role in global trade, with seaports being key gateways for goods. These ports are integrated with local infrastructure, including roads, railways, and power networks, as well as industry clusters and regional transport systems. Seaports facilitate intermodal transportation, linking maritime, rail, and road networks to provide seamless access to international markets and supply chains. Beyond facilitating trade, port operations drive economic growth by creating jobs and establishing vital connections between the hinterland and seaward markets.¹

There are approximately 4,764 ports worldwide, collectively responsible for over 80 percent of global trade.² Over the past 30 years, the global volume of seaborne trade has more than doubled. The preference for shipping, which accounts for about 90 percent of international cargo movement, stems from its cost-effectiveness and efficiency compared to alternative transportation systems.³

Seaports, integral to the global economy, are also evolving into vital hubs for significant coastal populations and critical maritime infrastructure with strategic importance. Notably, in 2005, 13 of the world's 20 most populous cities were port cities.

Maritime transport and ports are critical to India, a country with a rich history of trading across the seas. India is the sixteenth-largest maritime country in the world, with a coastline of 11,084 km. Currently, India has 12 major ports and more than 200 non-major ports. According to the Ministry of Ports, Shipping, and Waterways, around 95 percent of India's trading volume and 70 percent of its trade value is conducted via maritime transport⁴. In the fiscal year 2022, India's major ports had a capacity of 1.6 billion tonnes.⁵ During 2022–23, all major ports in India handled a total cargo volume of 1.3 billion tonnes.⁶ Maritime transport has been a catalyst for sustaining trade growth and the Blue Economy in India.

Despite their pivotal role, seaports are increasingly vulnerable to the adverse effects of climate change, manifested through rising temperatures and an uptick in the frequency and intensity of extreme weather events like flooding, heat waves, heavy precipitation, severe cyclones, and sea-level rise. Seaports, often located in environmentally sensitive and low-lying, high-risk areas, are susceptible to natural hazards. This vulnerability is expected to be exacerbated by the impacts of climate change. Approximately one-third of the world's ports are located in regions prone to tropical storms. Data from the World Port Index (1960–2016) indicates that nearly all ports in India are within 50 km of a tropical storm.⁷ The seamless operation of seaports is intricately linked to the dynamics of the ocean climate. Serving as crucial interfaces connecting maritime and inland transportation, any disruptions in port operations profoundly impact the port ecosystem and associated systems.

¹ Becker, A., Ng, A., McEvoy, D., & Mullett, J. (2018). Implications of climate change for shipping: Ports and supply chains. Wiley Interdisciplinary Reviews: Climate Change, e508. Retrieved from <https://core.ac.uk/download/pdf/212940731.pdf>

² UNCTAD. (2020). Review of Maritime Transport 2020. UNCTAD. Retrieved from <https://unctad.org/meeting/launch-review-maritime-transport-2020>.

³ Rajya Sabha Secretariat. (2018). Cargo Handling at the Major Ports (Two Hundred Sixty-Ninth Report). Ministry of Ports, Shipping and Waterways, Government of India. Retrieved from http://164.100.47.5/committee_web/ReportFile/20/109/269_2018_12_18.pdf

⁴ Ministry of Ports, Shipping and Waterways, Government of India. (n.d.). Ports Wing. Retrieved from <http://shipmin.gov.in/division/ports-wing>

⁵ Statista. (2023, October). Total cargo handling capacity at major ports across India from financial year 2013 to 2022. Retrieved from <https://www.statista.com/statistics/1189351/india-cargo-handling-capacity-at-major-ports/>

⁶ Statista. (2023). Total cargo handling capacity at major ports across India from financial year 2013 to 2022. Retrieved from <https://www.statista.com/statistics/686566/india-volume-of-cargo-in-ports/>

⁷ Becker, A., Ng, A., McEvoy, D., Mullett, J., (2018). Implications of climate change for shipping: Ports and supply chains. Wiley Interdisciplinary Reviews: Climate Change: e508. Retrieved from <https://doi.org/10.1002/wcc.508>

Contextualize Systemic Risk to the Seaport Ecosystem

Systemic risk stems from the potential threats posed by individual failures, accidents, or disruptions to a system through contagion.⁸ Although such events may originate from a breakdown in a subcomponent, leading to an individual failure, they are characterized by subsequent cascading effects that impact the broader system.⁹ These risks involve cascading and compounding effects that spread within and between various systems and sectors (such as ecosystems, health, and infrastructure). This occurs through the movement of people, products, money, and information across borders.

Systems that are susceptible to systemic risks are deeply interconnected and intertwined with one another. These interconnections contribute to complex causal structures and dynamic evolutions, often exhibiting non-linear cause-and-effect relationships, stochastic effects, and potentially global ramifications extending beyond borders.¹⁰ Systemic risk is characterized by its widespread impact, difficulty in predicting when it will occur, and magnitude. The risk often arises from the interconnectedness and interdependencies within a system, where the failure of one node can trigger a chain reaction that affects others. Furthermore, this risk is exacerbated by the lack of transparency and the complexity inherent in large, interconnected systems.

The seaport ecosystem, often situated in expansive coastal urban centres, comprises an intricate web of stakeholders, including shipping companies, port authorities, logistics providers, and government agencies. These systems grapple with multifaceted challenges that contribute to systemic risk. The concentration of global trade on a few major shipping lanes, the increasing size of cargo ships, and consolidation within the shipping industry heighten susceptibility to systemic shocks. This concentration risk means that disruptions at critical nodes can have a disproportionately large impact on global trade. For instance, congestion or delays in one port can trigger a domino effect globally, as modern economies are intricately interconnected, magnifying the impact of seaport disruptions. Refer to Figure 1.

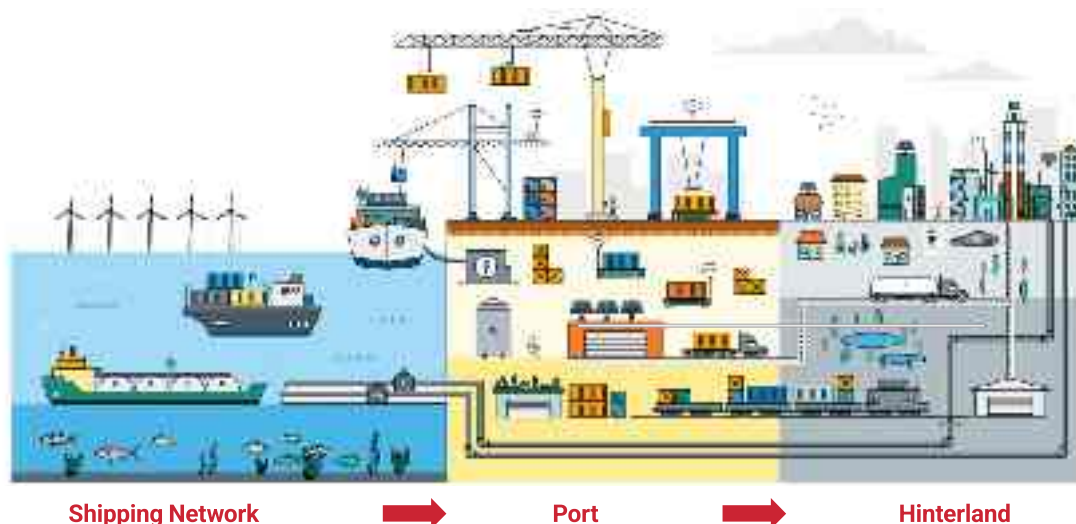


Figure 1: Landscape of seaport ecosystem

⁸ Centeno, M. A., Nag, M., Patterson, T. S., Shaver, A., & Windawi, J. A. (2015). The emergence of global systemic risk. *Annual Review of Sociology*, 41, 65-85. Retrieved from <http://www.annualreviews.org/doi/abs/10.1146/annurev-soc-073014-112317>

⁹ Kaufman, G. G., & Scott, K. E. (2003). What is systemic risk, and do bank regulators retard or contribute to it? *The Independent Review*, 7(3), 371-391.

¹⁰ Renn, O., Lucas, K., Haas, A., & Jaeger, C. (2019). Things are different today: The challenge of global systemic risks. *Journal of Risk Research*, 22(2), 401-415. Retrieved from <https://doi.org/10.1080/13669877.2017.1409252>.

Systemic Risk of Seaport in the Face of Climate Change

Climate change presents a formidable threat to seaport ecosystems. Rising temperatures and increased extreme weather events make ports increasingly vulnerable. These climate-induced disruptions extend beyond local boundaries, triggering systemic consequences for global shipping, trade, and supply chains. An analysis of climate-related downtime across 1,320 ports, integrated into a global transport flow model, reveals that systemic risks place an annual average of \$81 billion in global trade and at least \$122 billion in economic activity at risk each year.¹¹

By the 2070s, the total asset exposure in major global port cities is projected to increase significantly, reaching around \$35,000 billion—more than ten times the current levels.¹² This growth will be driven by climate change (including sea-level rise and increased storm activity), land subsidence, population growth, and rapid urbanization. Although cities in developed countries like the USA, Japan, and the Netherlands currently dominate in terms of asset exposure, the most rapid increases are expected in developing countries as economic development extends into high-risk flood-prone areas. These trends will substantially elevate the vulnerability of port cities, including those in India, to systemic risks. India, with its rich maritime heritage, faces several challenges related to climate change. The North Indian Ocean has experienced an approximate temperature rise of 0.7°C. Sea levels have risen from 1.06–1.75 mm/year between 1874 and 2004 to 3.3 mm/year from 1993 to 2017, aligning with the global sea level rise rate.¹³ This warming has contributed to the heightened intensity of tropical cyclones, as seen from 14 severe cyclones recorded in the past decade, causing widespread damage and socio-economic consequences. The frequency of storms surged by 52 percent, their duration extended by 80 percent, and their intensity increased by 20 percent before the monsoon season, followed by a 40 percent increase after the monsoon.¹⁴ These climate-related drivers not only endanger port infrastructure but also disrupt operations, resulting in extended downtime and significant economic losses.¹⁵



¹¹ Verschuur, J., Koks, E. E., & Hall, J. W. (2023). Systemic risks from climate-related disruptions at ports. *Nature Climate Change*, 13(10), 804–806. Retrieved from <https://doi.org/10.1038/s41558-023-01754-w>

¹² Nicholls, R. J., et al. (2007). Ranking port cities with high exposure and vulnerability to climate extremes: Exposure estimates. OECD Environment Working Paper, No. 1. Retrieved from https://www.researchgate.net/publication/5205894_Ranking_Port_Cities_with_High_Exposure_and_Vulnerability_to_Climate_Extremes_Exposure_Estimates

¹³ Krishnan, R., Sanjay, J., et al. (eds). (2020). *Assessment of Climate Change over the Indian Region*, A Report of the Ministry of Earth Sciences (MoES), Government of India. Singapore: Springer.

¹⁴ Details available at <https://eos.org/articles/climate-change-is-making-indias-west-coast-more-vulnerable-to-cyclones>

¹⁵ US Climate Change Science Program. (2008). *Impacts of climate change and variability on transportation systems and infrastructure: Gulf Coast study, phase I*. U.S. Government Printing Office. Retrieved from <http://www.climatechange.gov/Library/sap/sap4-7/final-report>

In a world marked by growing coastal populations, increasing seaborne trade, and changing climate dynamics, the vulnerability of port cities to climate-related extremes is destined to rise. The financial consequences of infrastructure damage and operational disruptions in interconnected global supply chains can be substantial, often resulting in significant costs and economic losses. The close connection between shipping lines, ports, and their hinterlands accentuates the potential ripple effects of disruptions, affecting the entire supply chain.¹⁶

Events such as Hurricane Katrina in 2005 and Hurricane Dorian in 2019 highlight the vulnerability of critical infrastructure, which has resulted in billions of dollars in losses.¹⁷ For instance, LaGrange's estimate indicated that the damages at the port of New Orleans due to Hurricane Katrina amounted to \$100 million, with businesses relying on the port incurring additional damage ranging from \$280 to \$300 million.¹⁸ The aftermath of Hurricane Katrina led to a four-month shutdown of the port,¹⁹ underscoring the systemic risk that extreme weather events pose to seaports. Similarly, the severe damage suffered by Chennai Port in India during the 2015 floods created a domino effect on the road and rail system, causing cascading disruptions throughout the supply chain, affecting importers, exporters, carriers, forwarders, warehouses, and container freight stations.²⁰ Cyclone Hudhud in 2014 caused \$31.5 million in damages to Visakhapatnam port,²¹ while Cyclone Phailin in 2013 resulted in \$60.6 million in damages to Gopalpur and Paradip ports.²² These examples underscore the critical need for resilient strategies to prevent cascading impacts and enhance the preparedness of ports and their surrounding areas.



¹⁶ Elsner, J. B., Kossin, J. P., & Jagger, T. H. (2008). The increasing intensity of the strongest tropical cyclones. *Nature*, 455, 92-95. Retrieved from <https://doi.org/10.1038/nature07234>. Emanuel, K. (2005). Increasing destructiveness of tropical cyclones over the past 30 years. *Nature*, 436, 686-688. Retrieved from <https://doi.org/10.1038/nature03906>.

¹⁷ MaZegarra, M. A., Schmid, J. P., & et al. (2020). Impact of Hurricane Dorian in the Bahamas: A view from the sky. Technical Note. Country Department Caribbean Group, Inter-American Development Bank. Retrieved from https://publications.iadb.org/publications/english/document/Impact_of_Hurricane_Dorian_in_The_Bahamas_A_View_from_the_Sky.pdf

¹⁸ Details available at <https://www.nytimes.com/2006/01/03/business/worldbusiness/new-orleans-port-is-getting-over-katrina.html>

¹⁹ Verschuur, J., Kirks, E. E., & Hall, J. W. (2020). Port disruptions due to natural disasters: Insights into port and logistic resilience. *Transport Resilience*, 85, 1-15

²⁰ Port Strategy. (2015, December 11). Chennai port operations crippled by floods. Retrieved from <https://www.portstrategy.com/news101/world/asia/chennai-port-operations-crippled-by-floods>.

²¹ Economic Times. (2014). Report on the financial impact of Cyclone Hudhud on Visakhapatnam Port. *Economic Times*

²² Business Standard. (2013). Examination of Cyclone Phailin's economic impact on Gopalpur and Paradip Port. *Business Standard*.

A survey of 350 major ports worldwide revealed that nearly 58 percent of respondents indicated that ports are currently designed based on historic 100-year storm periods.²³ Alarming, only 44 percent of global ports, mostly in developed countries, are adequately prepared for potential climate change impacts, highlighting a high-risk situation for these ports. The projected shift from a 100-year return period to a new 30-year return period due to climate change,²⁴ combined with an increased likelihood of extreme climate-related events, will exacerbate the situation. This challenge is further compounded by relative sea-level rise and ongoing business-as-usual trends in global greenhouse gas emissions.

Research Problem, Rationale, and Scope

International trade and the global supply chain heavily rely on seaports, which are critical hubs interconnected with various nodes and systems. These systems are characterized by closely intertwined interactions that ensure the continuous flow of information, money, goods, services, and people, thereby contributing significantly to the global economy.



As seaports expand to enhance their operational capabilities and become more efficient and larger, they simultaneously face increased risks from climate change. Ironically, the very systems that drive their efficiency—such as labour specialization, economies of scale, collective knowledge, connectivity, and information sharing—also make them more susceptible to catastrophic outcomes. Seaports, typically located in low-lying coastal regions with extensive interconnections to hinterland ecosystems, are particularly susceptible to climate-induced hazards. The cascading effects of port disruptions can lead to systemic risks within these interconnected systems, impacting global supply chains and economic stability. Addressing these multifaceted challenges is crucial to fostering resilience against systemic risks. Notably, there is a gap in research that specifically addresses this issue, emphasizing the novelty and significance of the current study.

An initial study titled ‘Assessing Climate Change Risk to and Resilience of India’s Seaport Infrastructure and Operations’, conducted by Pushp Bajaj and Chime Youdon under the Coalition for Disaster Resilient Infrastructure (CDRI) fellowship project, made a critical observation. The study noted that while ports in India often have well-formulated disaster management strategies, such as standard operating procedures during tropical cyclones, they currently lack dedicated and comprehensive climate change adaptation strategies. These strategies are essential to address evolving hydrometeorological disasters and the slow-moving yet high-impact threat of sea-level rise.

²³ Becker, A. (2013). Building seaport resilience for climate change adaptation: stakeholder perceptions of the problems, impacts, and strategies. PhD Thesis Submitted to the Interdisciplinary Program in Environment and Resources and the Committee on Graduate Studies of Stanford University. Retrieved from https://www.researchgate.net/publication/258995789_Building_Seaport_Resilience_for_Climate_Change_Adaptation_Stakeholder_Perceptions_of_the_Problems_Impacts_and_Strategies

²⁴ Becker, A. (2013). Building seaport resilience for climate change adaptation: stakeholder perceptions of the problems, impacts, and strategies. PhD Thesis Submitted to the Interdisciplinary Program in Environment and Resources and the Committee on Graduate Studies of Stanford University. Retrieved from https://www.researchgate.net/publication/258995789_Building_Seaport_Resilience_for_Climate_Change_Adaptation_Stakeholder_Perceptions_of_the_Problems_Impacts_and_Strategies

The increasing interconnectedness of global trade, coupled with the increasing unpredictability of climate-related events, exacerbates the risk of cascading failures resulting from port disruptions. Addressing this systemic risk is, therefore, of paramount importance. While there is a growing recognition of the necessity to view risks holistically, existing frameworks do not adequately demonstrate how to operationalize systemic risk management within port ecosystems. Developing a comprehensive framework to assess and manage these risks is imperative to safeguarding the critical functions of seaports in the global supply chain.

To address these identified gaps, the National Maritime Foundation (NMF), in collaboration with CDRI and Keio University, Japan, has initiated a project to develop a systemic risk assessment framework for the seaport ecosystem. This framework will be applied to five seaports in India, with a pilot study focusing on two major ports on the east coast: Paradip Port Authority and Visakhapatnam Port Authority.

The Paradip Port Authority and Visakhapatnam Port Authority are key economic hubs on India's eastern coast, handling significant cargo volumes annually, including coal, petroleum, and iron ore. Their strategic importance, efficient operations, and high throughput make them crucial for the region's economy. However, due to their coastal locations, both ports are vulnerable to climate-related hazards, specifically to cyclonic events. With its proximity to critical infrastructure, Visakhapatnam Port has a history of cyclonic storms, such as the devastating Cyclone Hudhud in 2014, which led to major operational disruptions and economic losses. Similarly, Paradip Port in Odisha has faced recurrent threats from cyclones, such as the 1999 Super Cyclone, and experienced significant impacts from cyclones Phailin, Hudhud, and Fani. According to the study 'Assessing Climate Change Risks to and Resilience of India's Seaport Infrastructure and Operations', these ports are exposed to the highest level of risk from cyclonic storms, including extremely severe cyclonic storms with wind speeds exceeding 168 km/h.

This assessment is further validated by the first-hand experiences of port authorities, such as the damage caused by Cyclone Hudhud at Paradip Port. The existing infrastructure, including cargo-handling equipment, storage areas, and administrative and residential buildings, are not designed to withstand



sustained wind speeds above 160 km/h. Moreover, over the past decade, India has experienced 14 severe cyclonic storms, with eight impacting the eastern coast. Notable storms include Phailin (2013), Hudhud (2014), Ockhi (2017), Titli (2018), Matmo (2019), Fani (2019), Amphan (2020), and Yaas (2021). These storms resulted in substantial damage, with an estimated total economic impact exceeding \$33 billion. Specific losses included approximately \$4.15 billion from Phailin, \$3.58 billion from Hudhud, \$915 million from Ockhi, \$920 million from Titli, \$8.1 billion from Fani, \$13.5 billion from Amphan, and \$2.7 billion from Yaas. The damages involved the inundation of low-lying areas, destruction of property, loss of livelihoods, devastation of natural coastal ecosystems, disruption of fishing and agriculture, erosion of beaches and embankments, and interruptions to electricity, road, rail, and port access.

Given the historical data and the severe impact of cyclones, this study focuses on cyclone-induced disruptions to port operations. By isolating a single hazard rather than examining multiple threats, the study seeks to develop a deeper understanding of the interdependencies and linkages within the components of port systems, thereby enhancing the depth of insights. The scope of this initial phase is limited to assessing systemic risks arising from tropical cyclones and associated flooding within Indian port ecosystems. In the second phase, the study will expand to examine the chronic impacts of sea level rise on the long-term functioning of these systems. To operationalize the proposed framework, pilot studies will first be conducted at Visakhapatnam Port Authority and Paradip Port Authority. Insights and lessons learned from these pilots will inform the refinement and broader application of the model to other key maritime nodes, including Mumbai Port Authority, Mundra Port, and Port Blair.

Given the limited availability of integrated data and the complex, dynamic nature of port ecosystems, the study adopts a cyclic input methodology. This iterative approach improves efficiency by breaking down complex tasks into manageable cycles and supports continuous learning through regular feedback loops. It also enhances flexibility, allowing the framework to adapt to changing conditions, and reduces risk by identifying and addressing issues early. Most importantly, it fosters continuous improvement, enabling the framework to evolve in response to emerging data, shifting environmental conditions, and stakeholder engagement—thus laying a robust foundation for long-term systemic risk management in Indian ports.



Objectives

The study aims to achieve the following three main objectives:

Objective – A

Develop a ‘Systemic Risk Assessment Framework for Seaport Ecosystem’ for the five ports:

- Visakhapatnam Port Authority (VPA)
- Paradip Port Authority (PPA)
- Mumbai Port Authority (MbPA)
- Mundra Port
- Port Blair

This framework will analyse interconnected resilience drivers to assess and understand the systemic risks and resilience of these critical seaport ecosystems during cyclones and associated flooding scenarios.

Objective – B

Initially implement the proposed framework at Visakhapatnam Port Authority and Paradip Port Authority. The insights and lessons learned from these pilot studies will be used to refine and apply the model to the Mumbai Port Authority, Mundra Port, and Port Blair.

Objective – C

Propose practical policy recommendations for planners and policymakers tailored to the specific contexts of each port while considering local-level capacities and limitations.







Methodology

Lorem ipsum

Building of Systemic
Risk Assessment Framework
for Seaports in India

The systemic risk assessment methodology is a comprehensive three-step approach designed to assess and understand the systemic risks and resilience of critical seaport ecosystems. This research methodology combines qualitative and quantitative techniques to deliver a detailed analysis of seaport infrastructure resilience. It serves policymakers, researchers, and stakeholders who face challenges such as coastal hazards. By using the systemic risk assessment survey, this approach offers a nuanced and detailed analysis of resilience across different systems. While the details of this methodology are discussed in a separate paper by the same authors, the high-level flow is captured in Figure 2.

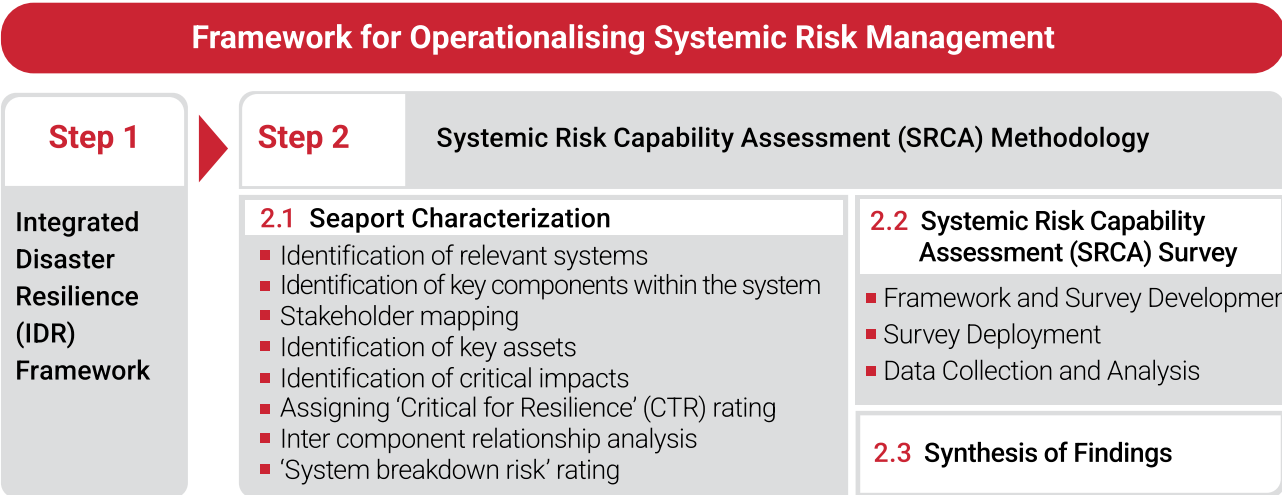


Figure 2: Quasi-quantitative framework for operationalizing systemic risk assessment for seaports

Step 1: Seaport Characterization

‘Seaport Characterization’, is the foundational stage of the assessment process. This stage identifies relevant systems within the seaport ecosystem and their interdependencies, ensuring a comprehensive assessment of systemic risks. It includes identifying key components within these systems, mapping stakeholders, identifying critical assets, and categorizing the impacts of coastal hazards. A ‘critical for resilience’ rating is assigned to components to prioritize risk management, and the inter-component relationships are analysed to identify pivotal elements. A ‘system breakdown risk’ rating is also proposed to guide resource allocation for resilience. Refer to Figure 3.

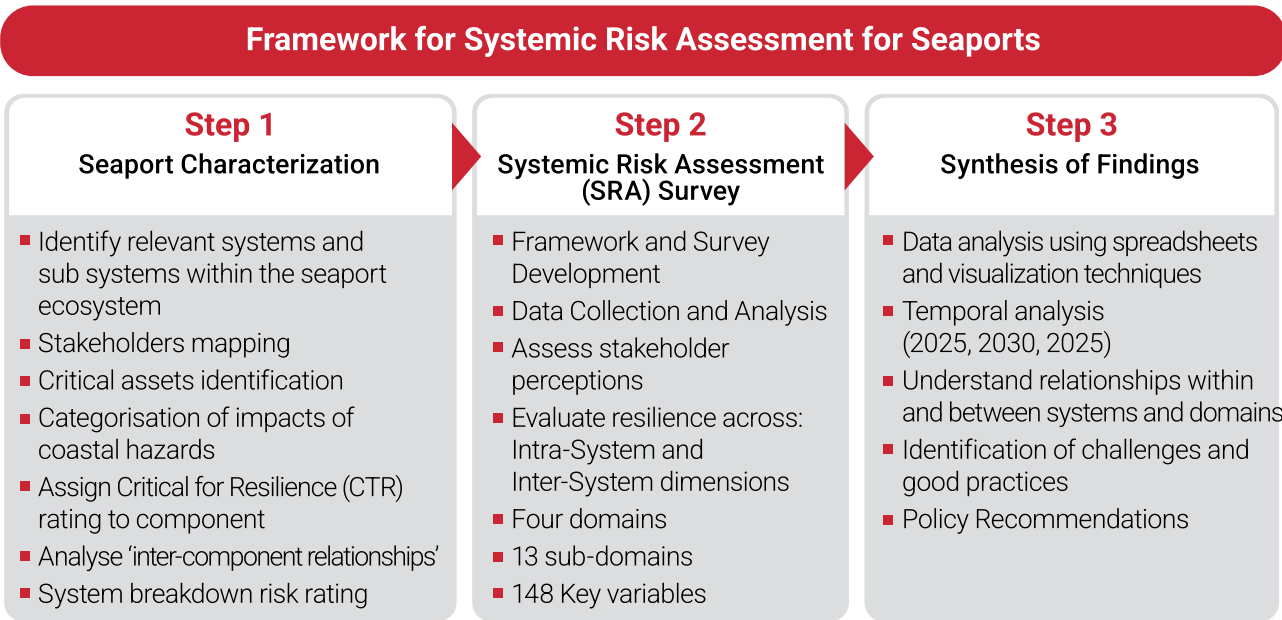


Figure 3: Framework for systemic risk assessment for seaports

Step 2: Systemic Risk Capability Assessment Survey

This structured approach includes the development of a framework and survey, as well as data collection and analysis. The survey assesses stakeholder perceptions and complements the findings from Step 1. It focuses on two dimensions of resilience: Intra-System and Inter-System. Additionally, it addresses four domains and 13 subdomains to capture the operational, strategic, and regulatory components of the ecosystem. The comprehensive survey questionnaire evaluates resilience across 148 key variables, spanning 2 dimensions (Intra- and Inter-System), 5 systems, 4 domains, 13 subdomains, 3 time scales. The deployment of the survey and subsequent data analysis offer policy guidance to enhance resilience.

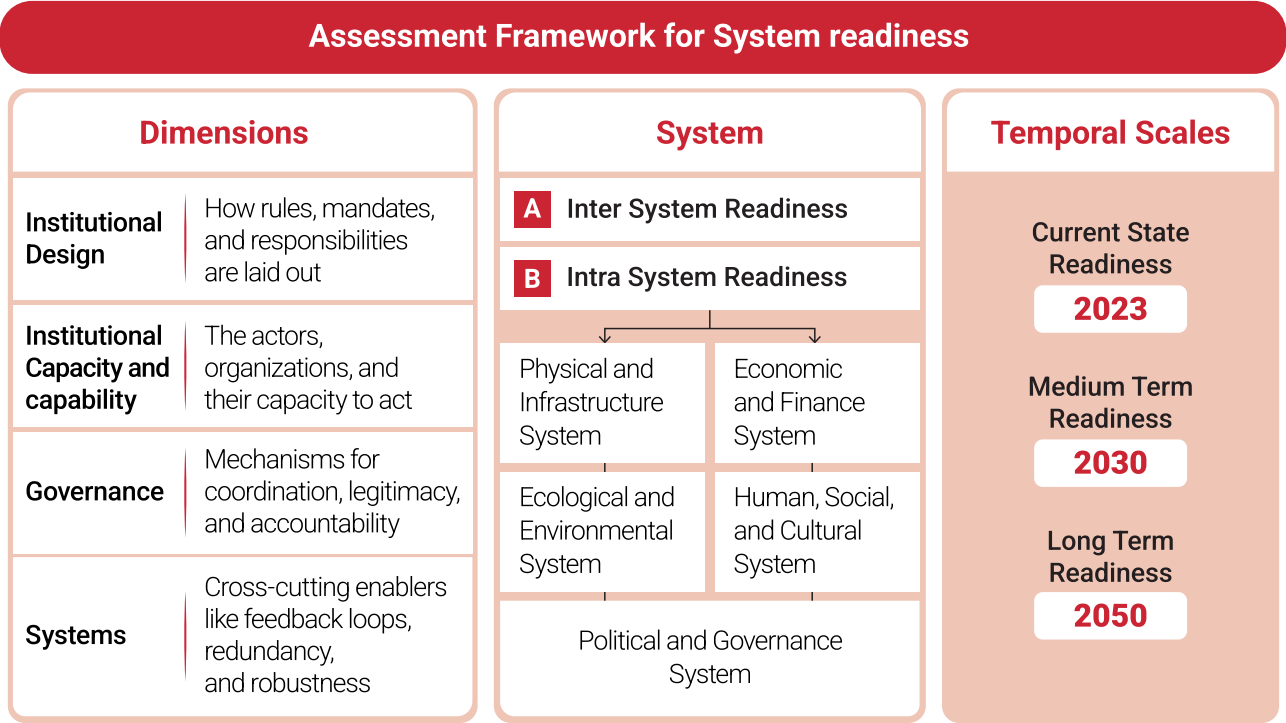


Figure 4: Schema for systemic risk capability assessment survey domains, systems, and temporal scales

Step 3: Synthesis of Findings

This step explores the data collected in Steps 1 and 2 through meticulous analysis using spreadsheets and visualization techniques. Temporal analysis over different time horizons (current, medium, and long term) provides insights into resilience trends. The synthesis enhances understanding of relationships within and between systems and domains. As a result, this holistic interpretation of findings aids decision-making and strategy development.

The systemic risk assessment methodology serves as a valuable tool for assessing and enhancing the resilience of seaport ecosystems. It combines theoretical framing, stakeholder perceptions, and data analysis across three steps to assess systemic risks and inform policy and strategy development. By focusing on key systems, components, stakeholders, assets, impacts, and interdependencies, this methodology offers a holistic understanding of seaport ecosystems, enabling decision-makers to address complex challenges.

Some of the research questions considered in this study are as follows:

1. Is there a vision and common charter for pursuing systemic risk management across all systems involved in port operations?
2. How well is systemic risk management integrated into the development and planning processes of port authorities, including disaster risk reduction and climate change adaptation?
3. How effective is inter-agency coordination in managing systemic risks within port ecosystems?
4. What are the main factors that impact the systemic resilience of the port ecosystem?
5. Do you evaluate the risk and severity of impacts on critical systems?
6. Have direct and indirect transboundary effects, such as contagion or spill-over effects, been mapped at both intra- and inter-system levels?
7. How comprehensive is incorporating multi-hazard risk assessments and scenario planning in determining systemic risk management portfolios, including singular, compound, cascading, and systemic risks?
8. How severe are the impacts, and how quickly can operations resume after incidents, especially in infrastructure, human factors, social and cultural aspects, economic and financial sectors, ecological and environmental concerns, and political and governance realms?
9. How effective are recovery strategies in restoring normal operations after an incident?
10. What measures are taken to ensure rapid recovery and minimize downtime during a systemic failure?



Analysis



The analysis section of the study examines the seaport ecosystem from two perspectives. First, an investigation is conducted through the lens of the seaport characterization, and second, the findings of the systemic risk assessment survey are synthesized.

Analysis of Seaport Characterization

This section is based on a detailed analysis of the complexities within the Visakhapatnam Port Authority and Paradip Port Authority, with each of the five systems playing a crucial role in port functionality and interconnectivity. Additionally, this is essential for a comprehensive assessment of systemic risks. Furthermore, the top four components were identified within each system, resulting in 20 components. This identification was a critical step in understanding the multifaceted dynamics of the seaport ecosystem. These components were selected based on their centrality to port functionality, interconnectedness with other systems, and the overall influence on the resilience and efficiency of port operations. This targeted approach, refined through an extensive literature review and consultations, ensured a focused assessment of systemic risks within the seaport ecosystem. Additionally, stakeholder mapping within these systems was conducted to understand the diverse range of entities and individuals influencing or influenced by the port’s operations. Lastly, critical assets within these systems were identified and mapped. This step involved a detailed mapping of key assets within the port environments and categorizing them across three spatial domains: seaside, portside, and hinterland. This comprehensive cataloguing aimed to create a holistic spatial representation of the port’s assets, facilitating an in-depth analysis of how these assets interact within and across the systems, thereby contributing to the overall functionality and resilience of the port. Steps A to H discussed below represent the output of this analysis:

A Identification of relevant systems

This step aimed to identify the key systems in the seaport ecosystem. To achieve this goal, five critical systems were identified (as depicted in Table 1): **Physical and Infrastructure, Economic, Human, Cultural and Social, Environmental and Ecological, and Political and Governance.**

Table 1: Key systems identified in the seaport ecosystems

S No.	Systems
1	Physical and Infrastructure System
2	Human, Social, and Cultural System
3	Economic and Finance System
4	Ecological and Environmental System
5	Political and Governance System

The rationale for selecting these five systems for this study stems from a detailed analysis of the seaport ecosystem’s complexity. These systems were selected based on their integral roles in seaport functionality and their interconnectivity, which are essential for a comprehensive assessment of systemic risks. The Physical and Infrastructure system forms the backbone of port operations, while the Economic system underpins the commercial viability. The Human, Cultural, and Social system reflect human capital and community interactions. The Environmental and Ecological system is crucial for sustainable operations, and the Political and Governance system provides the regulatory framework and policymaking (refer to Table 1). This selection process aimed to encompass all critical aspects of seaport ecosystems, ensuring the study adequately reflects the multifaceted interactions and dependencies that define their resilience and vulnerability to various challenges.

B Identification of key components within the system

In this section, the key components were identified within the Visakhapatnam Port Authority and Paradip Port Authority seaport ecosystem, as depicted in Table 2, laying the foundation for an in-depth analysis of the systemic risk assessment methodology’s comprehensive framework.



Table 2: Key components identified within the five identified systems in the seaport ecosystem

Systems	Components	Contextualization in Seaport Ecosystem
Physical and Infrastructure	Transportation networks	Essential for the movement of goods and connectivity with global supply chains; directly impacts the port's operational capacity
	Energy infrastructure	Provides the necessary power for all port operations and is critical for maintaining continuous activity
	Telecommunications infrastructure	Facilitates the flow of information, which is vital for logistics, coordination, and emergency response
	Water supply and sanitation systems	Ensures the health and safety of port workers and the cleanliness of the port environment
Human, Social, and Cultural	Education system	Schools, colleges, and training centres to support the education of port employees' children and provide skill development for port staff, enhancing operational efficiency and safety
	Healthcare system	Critical for maintaining the well-being of port employees and handling any on-site emergencies
	Social welfare programmes	Enhance the well-being of port employees and the wider community, providing essential support and financial security for both workers and their families
	Cultural diversity	Shapes the integration of port operations into the local community and can impact international relations by fostering global connections and understanding
Economic and Finance	Trade and Commerce	Directly linked to the port's primary function and economic contribution through the facilitation of imports and exports
	Banking and financial institutions	Facilitate financial transactions, provide essential trade financing, offer risk management services through insurance, and contribute to the overall economic infrastructure that supports international trade and port operations
	Labour market and employment	The availability of a skilled workforce is vital for efficient port operations, driving productivity and safety while boosting the economic vitality of the surrounding region through job creation and local economic activity
	Industrial and manufacturing sectors	The port serves as a critical hub for the import and export of industrial goods, directly influencing the economic activities and growth of the industrial and manufacturing sectors
Ecological and Environmental	Biodiversity and ecosystems	The ecological health of the port's surrounding environment, including its biodiversity and interconnected ecosystems, is vital for sustainability, resilience, and regulatory compliance
	Air and water quality	Ports impact local air and water quality through emissions and runoff, making it essential to adhere to strict environmental regulations to minimize their environmental footprint
	Pollution control and environmental regulations	Adhering to pollution control measures and environmental regulations is vital for minimizing impact, ensuring compliance, sustaining port operations, and promoting a cleaner environment
	Climate change and mitigation strategies	Mitigating the effects of climate change by implementing strategies that enhance resilience, reduce environmental impact, and ensure the safety and functionality of port operations amid rising sea levels and extreme weather is crucial
Political and Governance	Government structure	Defines the port's operational framework, influencing both day-to-day activities and long-term strategic development
	Policy and regulation, standards and building codes	Establishes the legal and operational boundaries within which the port must operate, setting guidelines for safety, environmental standards, and construction
	Public administration and bureaucracy	The efficiency of administrative processes within the port authority, including permitting, decision-making, and regulation enforcement, can significantly affect the port's ability to facilitate trade and comply with regulations
	Law enforcement and security forces	Ensures the security of the port's assets, personnel, and operations against threats, illicit activities, and disasters

C Stakeholder Mapping

The next step was to identify the key stakeholders of the 20 components within the five systems under study - within the context of the Visakhapatnam Port Authority and Paradip Port Authority ecosystem, as depicted in Table 3.



Table 3: Key stakeholders within the components of the seaport ecosystem

Systems	Components	Primary Stakeholder	Secondary Stakeholder
Physical and Infrastructure	Transportation networks	Navigational buoys, pilot boats, breakwaters, dockyards, dredging equipment, marine fuelling stations	Railroads, roadways, truck carriers, shippers, freight forwarders, logistic providers, ship management companies, cargo owners, shipyards
	Energy infrastructure	Offshore wind turbines, buoys, single-point mooring	Regulatory bodies, state government
	Telecommunications infrastructure	Undersea cables, marine communication systems	Shipping operators, port operators, terminal operations
	Water supply and sanitation systems	Desalination plants, ballast water treatment	Health departments, Environmental agencies, port operators, state government, supply and management operators, regulators
Human, Social, and Cultural	Education system	Marine training centres	Students, port employees, teachers, trainers, administrators
	Healthcare system	First-aid stations	Port employees, emergency services, and administrators
	Social welfare programmes	Seafarer welfare facilities	Non-governmental organization, local communities
	Cultural diversity	Cultural exchange centres	Local communities, tourism boards
Economic and Finance	Trade and Commerce	Customs inspection points, fishing cooperatives, seafood trade associations, and inspection facilities for fishing vessels upon arrival/departure	Importers/exporters, trade associations, business owners, consumers
	Banking and financial institutions	ATMs	Commodity traders, investment firms, and individual investors
	Labour market and employment	Recruitment agencies for seafaring personnel, local fishing crew agencies	Labour unions, workforce development centres, project contractors
	Industrial and manufacturing sectors	Offshore assembly platforms, offshore fish farms, and aquaculture platforms	Suppliers, distributors, port operators
Ecological and Environmental	Biodiversity and ecosystems	Coral reefs, tidal marshes, mangrove forest areas, seagrass meadows, kelp forests	Research institutions, civil society organizations, port-level, state-level, and central government agencies
	Air and water quality	Water sampling stations, marine pollution monitoring stations	Public health departments, community, CSOs
	Pollution control and environmental regulations	Oil spill response equipment, bioremediation systems	Port Authority, CSOs, state and central government agencies
	Climate change and risk mitigation strategies	Sea wall barriers, surge protection systems, coastal wetlands	Environmental non-governmental organization, local government, state and central government agencies
Political and Governance	Government structure	Lighthouses, navigation centres, buoy systems, AIS systems, coastal monitoring stations	Port-level, municipal-level, district-level, state government
	Policy and regulation	Port authority safety regulations department, maritime pollution control, vessel traffic management systems (VTMS), environmental monitoring stations, port security policy enforcement	Policymakers and regulators at local, state, and central government
	Administrative Departments	Visa processing centres, permitting offices, immigration control offices	Government clerks, bureaucrats
	Law enforcement and security forces	Port security offices, patrol boats, naval bases, coast guard stations	Coast guard, police, security agencies

D Identification of key assets

The subsequent phase, known as ‘asset mapping’, involved identifying the key assets in the seaport ecosystem across the seaside, portside, and hinterland within the Visakhapatnam Port Authority and Paradip Port Authority, as detailed in Table 4.

Table 4: Key assets within the components of the seaport ecosystem within Visakhapatnam Port Authority and Paradip Port Authority ports

Systems	Components	Seaside Hard Assets	Portside Hard Assets	Hinterland Hard Assets
Physical and Infrastructure	Transportation networks	Navigational buoys, pilot boats, breakwaters, dockyards, dredging equipment, marine fuelling stations	Cranes, container terminals, jetties, storage facilities, customs, and inspection facilities	Roadways, railroads, truck fleets, intermodal transport terminals, freight corridors
	Energy infrastructure	Offshore wind turbines, buoys, single-point mooring	Power distribution grids, Backup generators	Power plants, electrical substations
	Telecommunications infrastructure	Undersea cables, marine communication systems	Port communication towers, data processing centres, control centres	Telecommunication networks, satellite dishes
	Water supply and sanitation systems	Desalination plants, ballast water treatment	Potable water systems, Waste treatment facilities	Water towers, sewage treatment plants
Human, Social, and Cultural	Education system	Marine training centres	Port operation schools, safety training facilities	Vocational schools, universities
	Healthcare system	First-aid stations	Port health centres, emergency response teams	Hospitals, clinics
	Social welfare programmes	Seafarer welfare facilities	Employee assistance centres	Social service offices, community centres
	Cultural diversity	Cultural exchange centres	Multicultural centres, event venues	Community halls, festival grounds
Economic and Finance	Trade and Commerce	Customs inspection points, fishing cooperatives, seafood trade associations, and inspection facilities for fishing vessels upon arrival/departure	Trade offices, export processing zones, free trade zones, seafood storage, distribution centres for exports	Inland depots, commercial business centres
	Banking and financial institutions	ATMs	Bank branches, currency exchange centres	Financial hubs, insurance companies, investment firms
	Labour market and employment	Recruitment agencies for seafaring personnel, local fishing crew agencies	Port employment offices, union headquarters	Job training centres, labour housing, employment agencies
	Industrial and manufacturing sectors	Offshore assembly platforms, offshore fish farms, and aquaculture platforms	Warehousing, manufacturing facilities, cold storage facilities of seafood, packaging units	Industrial parks, distribution hubs, logistics centres, research and development centres, and transportation and fleet management systems



Systems	Components	Seaside Hard Assets	Portside Hard Assets	Hinterland Hard Assets
Ecological and Environmental	Biodiversity and ecosystems	Coral reefs, tidal marshes, mangrove forest areas, seagrass meadows, kelp forests	Green belt areas, habitat restoration sites, wetland buffer zones	Natural reserves, wildlife corridors, freshwater reserves
	Air and water quality	Water sampling stations, marine pollution monitoring stations	Air quality monitoring systems, effluent processing, stormwater management systems	Air filtration plants, water purification systems, wastewater treatment facilities
	Pollution control and environmental regulations	Oil spill response equipment, bioremediation systems	Hazardous waste disposal facilities, environmental monitoring stations, anti-pollution barriers	Recycling centres, Composting facilities, e-waste recycling facilities
	Climate change and mitigation strategies	Sea wall barriers, surge protection systems, coastal wetlands	Rainwater harvesting systems, solar panel arrays, green roofs, wind turbine installations	Drought-resistant landscaping, reforestation areas, carbon capture and storage projects, sustainable agriculture initiatives
Political and Governance	Government structure	Lighthouses, navigation centres, buoy systems, AIS systems, coastal monitoring stations	Port authority buildings, customs offices, security coordination centres, port authority operational centres	Municipal buildings, governmental oversight offices, regulatory bodies, international trade and regulation oversight bodies
	Policy and regulation	Port authority safety regulations department, maritime pollution control, vessel traffic management systems (VTMS), environmental monitoring stations, port security policy enforcement	Cargo inspection and control facilities, security and risk management offices, trade and sanction compliance units, port environmental impact assessment, and trade compliance units	International trade regulation offices, port development and infrastructure planning agencies, local and regional economic policy units, research and development centres, legal aid services, customs trade facilitation offices, sustainability policy agencies
	Public administration and bureaucracy	Visa processing centres, permitting offices, immigration control offices	Administrative buildings, permitting offices, tax offices, customs compliance offices	Public records archives, public service offices, government transparency offices
	Law enforcement and security forces	Port security offices, patrol boats, naval bases, coast guard stations	Police stations, checkpoints, security training facilities, CCTV surveillance systems, customs inspection points	Police stations, checkpoints, security training facilities, emergency response teams, cybersecurity units

E Identification of critical impacts

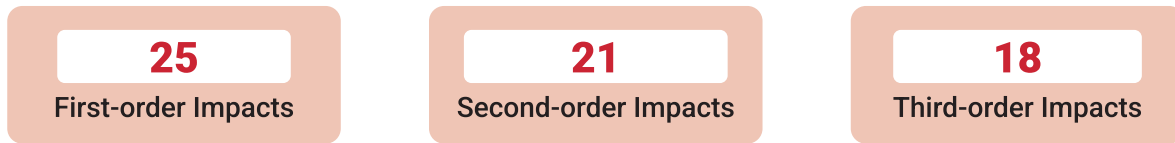
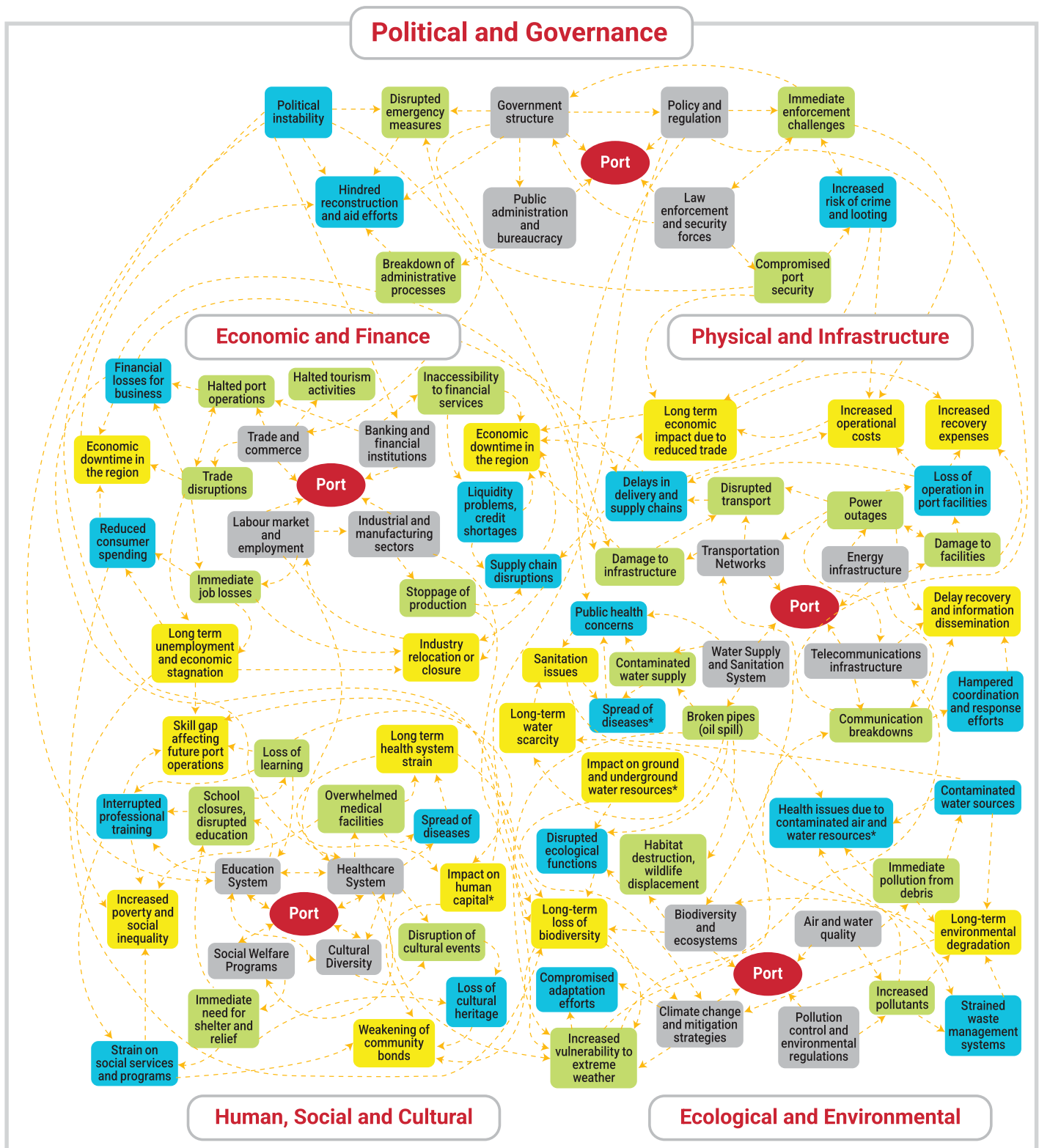
Understanding the resilience of the seaport ecosystem against severe cyclonic storms and long-term climate change is essential for ensuring the sustainability of Visakhapatnam Port Authority and Paradip Port Authority. A key aspect of this assessment involves identifying the most critical nodes within the port network—those with the most connections and significant influence on overall stability. By analysing the relationships among components and evaluating each node’s connectivity, it is possible to determine which elements play a pivotal role in maintaining the system’s integrity and stability.

Nodes that function as hubs—linking multiple components and facilitating diverse connections—are generally the most central and influential. These central nodes not only have numerous direct connections but also generate cascading effects across the network when disrupted. This step integrates historical data and expert consultations to capture both perceived and projected impacts of environmental challenges. The impacts are categorized into three levels:

- 1 First-order impacts** Directly affect the port’s immediate operations, primarily operational disruptions caused by severe weather events.
- 2 Second-order impacts** Indirect and cascading effects on interconnected systems within the port, including economic repercussions, social implications, and supply chain disruptions.
- 3 Third-order impacts** Long-term systemic changes in the port’s operational environment due to gradual climate change, posing significant challenges to sustainability and long-term planning.



A total of 64 impacts (refer to Figure 5) were identified across 20 components, categorized into 64 distinct impacts:



● 1st Order Impacts ● 2nd Order Impacts ● 3rd Order Impacts

The analysis identifies several key nodes that play a central role within the seaport ecosystem due to their connections and the potential cascading effects of disruptions. Table 5 summarizes these critical nodes, their significance, and their interconnections.

Table 5: Central nodes in the seaport ecosystem, their significance, and connections

Significance	Central Node	Connections
Directly influences the flow of goods, people, and resources. Disruptions can halt logistics, leading to economic delays and increased costs.	Transport Network	Roadways, railways, airports, port infrastructure, trade, healthcare, supply chains
Essential for powering industries, transport, and households. Interruptions affect industrial production, social services, and emergency response.	Energy Infrastructure	Manufacturing, residential power, industrial output, emergency services
A hub for economic activity, trade, and logistics. Disruptions impact supply chains, economic stability, and community services.	Port Operations	Transport network, energy supply, financial services, workforce availability
Support workforce skills and social well-being. Disruptions can weaken labour availability and community resilience.	Education and Healthcare Systems	Social stability, workforce development, skilled labour attraction
Represents individuals dependent on the port for livelihoods. Disruptions affect housing, employment, and social services.	Port Community	Housing, water supply, employment, social services, healthcare
Drive economic activity. Disruptions impact production, local economies, and financial stability.	Trade and Industrial Sectors	Infrastructure, labour, supply chains, finance
Critical for economic recovery. Limited financial support can delay rebuilding and worsen economic impacts.	Financial Institutions	Investment, disaster recovery, industrial and community rebuilding
Central to disaster response and policy reforms. Essential for maintaining public safety and regulatory oversight.	Government and Law Enforcement	Regulatory bodies, disaster management agencies, and social systems
Essential for sustainable development and resilience. Damage to ecosystems leads to long-term social and economic consequences, including loss of natural defences against storms, coastal erosion, and water regulation issues.	Biodiversity and Ecosystems	Agricultural productivity, pollution control, tourism, coastal ecosystem stability, natural storm barriers, water regulation, and coastline stability

Analysis of Central Nodes and their Impacts

The port emerges as the most critical node in the network, serving as the backbone of trade, economic stability, governance, infrastructure, and environmental sustainability. Its resilience is paramount, as disruptions at the port lead to cascading failures across interconnected systems. The transportation network is another vital node, facilitating the movement of goods, people, and resources. Any disruption—whether caused by extreme weather, infrastructure failures, or policy inefficiencies—can halt logistics, increase costs, and impact trade flows. Similarly, energy infrastructure is indispensable, as ports and industries rely on uninterrupted power supply for smooth operations. Power outages can paralyse port functions, disrupt supply chains, and affect broader economic sectors.

The financial sector, including banking and insurance institutions, plays a crucial role in recovery and adaptation. A lack of financial resilience can delay reconstruction efforts, leaving industries and communities vulnerable to long-term economic distress. Trade and commerce, along with industrial and manufacturing sectors, drive economic activity, making them key nodes. Disruptions in these areas can lead to job losses, financial instability, and weakened supply chains. Additionally, the education and healthcare systems are critical for human capital development and emergency response, as disruptions can have long-term socio-economic consequences. Furthermore, coastal ecosystems and biodiversity also serve as natural barriers against extreme weather events, providing essential services such as flood protection, water regulation, and coastline stability. The degradation of these ecosystems increases climate vulnerabilities, making ecosystem protection a key focus for policy initiatives.

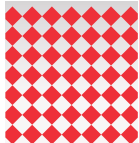


F **Assigning ‘critical for resilience’ rating**

In this section, an analysis was conducted on the critical for resilience rating of various components within the seaport ecosystems of the Visakhapatnam Port Authority and Paradip Port Authority. This evaluation was conducted using a series of decision matrices designed to ascertain the resilience criticality of seaport components at three distinct impact levels. These matrices cross-referenced the severity of each component’s impact on seaport operations (impact severity or IS) with the challenges encountered in restoring the component to normal operations post-impact (recovery difficulty or RD). This analysis considered both immediate (combined first and second order) and systemic, long-term (third order) impacts.

Impact severity is defined based on the duration of disruption it causes to seaport operations. The duration categories help to quantify the severity of the impact in terms of its immediate effects on the operational efficiency of the seaport.

Recovery difficulty is defined based on the duration and effort required to restore seaport components to their normal operational state following an impact. The duration categories help to quantify the complexity and resource demands associated with recovery efforts. Refer to the table below.

Impact Description	Impact Severity	Recovery Difficulty	3rd Order Systemic Impact Severity (SIS)	3rd Order Systemic Recovery Difficulty (SRD)	
Low Impact Severity	Port operation down for hours	Restoration takes less than 1 day	Impacts last for days to weeks	Recovery efforts take days to weeks	
Medium Impact Severity	Disruption last for 1-3 days	Restoration takes 1-3 days	Impacts last for weeks to months	Recovery efforts take weeks to months	
High Impact Severity	Disruption last more than 3 days to weeks	Restoration takes more than 3 days to weeks	Impacts last for months to years	Recovery efforts take months to years	

Decision Matrices

These matrices combine impact severity and recovery difficulty to assign a criticality rating. The decision matrices look at the following:

- The immediate impacts (first and second order) on operational efficiency.
- The long-term, systemic impacts (third order), which are more difficult to recover from.
- Climate change-related factors (e.g., rising sea levels, cyclones, altered rainfall) are considered as additional aspects that affect the long-term resilience of seaport components.

Criticality Ratings

The analysis categorizes seaport components into three distinct ratings:

1 High criticality

Components with both high impact severity and/or high recovery difficulty. These components are vital for seaport functionality, and their failure would significantly disrupt operations.

2 Medium criticality

Components with medium impact severity and/or recovery difficulty. While they are important, the failure of these components would have a less severe or more manageable impact.

3 Low criticality

Components that have low impact severity and recovery difficulty. These components are less crucial regarding resilience because their failure would not severely disrupt operations, and recovery would be relatively easy.

After the initial categorization, expert insights are integrated to ensure the accuracy of the ratings. These insights help refine the assessment, particularly for complex or ambiguous components.

Table 6 presents the results of the analysis, categorizing components based on the combined effect of impact severity and recovery difficulty across all three orders of impact: **immediate, systemic, and long term**.

Table 6: Critical for resilience ratings by components in the seaport ecosystem

Components	Impact Severity	Recovery Difficulty	3 rd Order SIS	3 rd Order SRD
Transportation networks				
Energy Infrastructure				
Telecommunications infrastructure				
Water supply and sanitation systems				
Education system				
Healthcare system				
Social welfare programs				
Cultural diversity				
Trade and Commerce				
Banking and financial institutions				
Labour market and employment				
Industrial and manufacturing sectors				
Biodiversity and ecosystems				
Air and water quality				
Pollution control and environmental regulations				
Climate change and adaptation strategies				
Government structure				
Policy and Regulation				
Public administration and bureaucracy				
Law enforcement and security forces				

The components of **Transportation Networks, Energy Infrastructure, Telecommunications Infrastructure, Healthcare Systems, Social Welfare Programmes, Trade and Commerce, and Biodiversity and Ecosystems** all exhibit high **impact severity** and **recovery difficulty** in the short and longterm. This underscores their critical role in societal functioning and the challenges climate change poses.

Transportation Networks experience severe short-term impacts during extreme weather events such as cyclones, floods, or storms, which can disrupt the movement of goods and people. Recovery from these events is complex and resource-intensive, requiring infrastructure repairs and replacements. In the long term, these systems face compounded risks from rising sea levels, coastal erosion, and increased storm frequency, making restoration efforts even more challenging. The cost and time required to adapt and ensure resilience against these evolving threats are considerable.



Similarly, **Energy Infrastructure** is highly vulnerable to short-term disruptions, particularly during power outages caused by extreme weather. The recovery process can be challenging due to the technical and logistical difficulties associated with restoring power, especially in remote or heavily impacted areas. Over time, climate-induced events like heat waves, floods, and wildfires will put additional pressure on energy systems, necessitating significant investment in more resilient and sustainable energy infrastructure. Adapting to these changes is expensive and requires innovative solutions to future-proof energy systems.



Telecommunications Infrastructure faces similar challenges. While short-term disruptions may lead to medium to high impact severity, long-term risks such as rising sea levels, severe storms, and extreme temperatures could severely affect telecommunications networks. The recovery of these systems is becoming increasingly difficult as they are becoming more complex and integrated into daily life. Restoring communication systems in the face of climate change will require advanced technology and significant investment to ensure they can withstand future disruptions.



The **Healthcare System** is another critical component that experiences high impact severity both in the short and long term. In the short term, healthcare facilities can be overwhelmed by disasters, disease outbreaks, or other emergencies, requiring substantial time and resources for recovery. Long-term impacts from climate change, such as increased frequency of heat waves, flooding, and the spread of vector-borne diseases, will further strain health services. The challenges of recovery in this context are compounded by the need for upgraded healthcare infrastructure, emergency preparedness, and adaptation strategies to address these evolving threats.



Social Welfare Programmes are essential for maintaining social stability, but they face significant challenges. Short-term disruptions, such as displacement caused by climate-induced disasters or sudden increases in vulnerable populations, require immediate intervention and substantial resources. In the long term, welfare systems will experience increasing strain due to factors like population displacement, rising poverty levels, and worsening inequality, making recovery efforts even more difficult. Systemic reforms and robust funding are essential to ensure these programmes remain effective in the face of climate change.



Trade and Commerce are significantly affected by disruptions in transportation networks, energy infrastructure, and telecommunications. Short-term impacts, such as shipment delays, damage to ports, or logistical bottlenecks, can halt trade operations and may require extensive repair work for recovery. Long-term climate impacts, including changing trade routes due to sea-level rise or increased supply chain disruption from extreme weather events, further exacerbate these challenges, making recovery more difficult. As the global economy becomes increasingly interconnected, the resilience of trade systems is critical for maintaining economic stability.



Finally, **Biodiversity and Ecosystems** face both short-term and long-term high-impact severity. Disasters and environmental degradation due to climate change – such as deforestation, flooding, or ocean acidification – cause immediate harm to these ecosystems. In the long term, the compounding effects of climate change, including habitat destruction, species extinction, and ecosystem collapse, make the recovery of biodiversity and ecosystems extremely difficult. Restoring these systems requires massive conservation efforts, rehabilitation programmes, and international collaboration to mitigate the long-term damage caused by climate change.



The components of **Water Supply and Sanitation Systems, Labour Market and Employment, Industrial and Manufacturing Sectors, Pollution Control and Environmental Regulations, Climate Change and Adaptation Strategies, Policy and Regulation, Public Administration and Bureaucracy, and Law Enforcement and Security Forces** exhibit medium to high impact severity in the short term. Although these components experience medium impact severity in the short term, their third-order impact severity and recovery difficulty become critical due to the long-term, systemic effects of climate change. The challenge of rebuilding and adapting these sectors to climate change demands extensive policy changes, infrastructure investments, and capacity building, making recovery a prolonged and complex process.

G Inter-Component Relationship Analysis

In this section of the study, the inter-component relationship analysis played a pivotal role in elucidating the complex web of interconnections within the seaport ecosystem of the Visakhapatnam Port Authority and Paradip Port Authority. This part of the methodology focused on mapping the operational interdependence among various components of the seaport ecosystem to understand how each component is functionally interconnected with others. This analysis identified specific components that displayed high interdependence, marking them as critical nodes within the system. The significance of these nodes lies in their ability to substantially impact other components, either positively or negatively, based on their performance or failure. Refer to Table 7.

Systems	Physical & Infrastructure	Human, Social, and Cultural	Economic and Finance	Ecological and Environmental	Political and Governance
Components	A1: Transportation	B1: Education	C1: Trade	D1: Biodiversity	E1: Government
	A2: Energy	B2: Healthcare	C2: Banking	D2: Air and Water Quality	E2: Policy
	A3: Telecom	B3: Social Welfare	C3: Labour and Market	D3: Pollution Control	E3: Public Admin.
	A4: Water Systems	B4: Cultural Div.	C4: Ind. & Mfg.	D4: Climate Strategies	E4: Law Enforcement

Table 7: Inter-component relationship in the seaport ecosystem

Systems		Physical and Infrastructure				Human, Social and Cultural				Economic and Finance				Ecological and Environmental				Political and Governance			
Components Interconnected with		A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4	D1	D2	D3	D4	E1	E2	E3	E4
Impacting Factors	A1																				
	A2																				
	A3																				
	A4																				
	B1																				
	B2																				
	B3																				
	B4																				
	C1																				
	C2																				
	C3																				
	C4																				
	D1																				
	D2																				
	D3																				
	D4																				
	E1																				
	E2																				
	E3																				
	E4																				

- H:

Indicates that the operation of one component is highly dependent on, or significantly impacts, another component. For example, “A1 (Transportation)” has a high interdependence with “A2 (Energy)”, indicating that transportation networks heavily rely on the energy infrastructure.
- M:

A moderate level of operational connection or impact
- L:

Implies minimal or indirect operational connections



The analysis of the operational interdependence (OI) among the various components of the seaport ecosystem reveals the intricate web of functional relationships that sustain the system's operations. This mapping exercise categorizes the components based on their level of interdependence, highlighting critical nodes with high levels of dependency across multiple areas.

Identification of Critical Nodes

Several components demonstrate a significant degree of dependency on other systems, indicated by red indicators in the matrix. These include elements within Physical and Infrastructure (A1, A2), Human, Social, and Cultural (B1, B2), Ecological and Environmental (D1, D3), and Political and Governance (E1, E2). This mapping highlights components with high interdependence as critical nodes within the seaport ecosystem. Their significance stems from the potential impact their performance or failure can have on other components. These components have been identified as crucial within the operational network of the ports, making them key focal points in risk management and resilience strategies. For instance:

Energy Infrastructure (A2): Given its high interdependence, any failure here can severely affect other systems, such as transportation, port operations, and social services.

Law Enforcement and Security (E1): With extensive connections across infrastructure and social systems, disruptions could impede disaster response and public safety.

Biodiversity and Ecosystems (D1): This component's impact on environmental health has far-reaching consequences for agriculture, public health, and tourism, especially in the long term.



H ‘System breakdown risk’ rating

In this section of the study, the system breakdown risk rating of components emerged as a pivotal aspect of the analysis. The approach employed a bespoke decision-making matrix that integrates two pivotal dimensions—criticality to resilience and operational interdependence impact—to accurately appraise the risk of system breakdown for each component. By systematically cross-referencing these dimensions, the matrix indicates key risks, guiding targeted resource allocation and strategic planning to improve the resilience of vital system components. This comprehensive approach enabled us to systematically evaluate the potential risks associated with each component. The output of this matrix, which was further validated through consultations with experts, provided critical insights into the resilience of the seaport ecosystem at both the Visakhapatnam Port Authority and Paradip Port Authority. Table 8 presents the output of this analysis.

Lorem ipsum

Table 8: System breakdown risk rating for seaport ecosystem components

Components	Criticality to Resilience	Operational Interdependence Impact	System Breakdown Risk Rating	Priority for Intervention
Transportation Networks	High	High	Very High	Immediate
Energy Infrastructure	High	High	Very High	Immediate
Telecommunications Infrastructure	Moderate	High	High	High
Water Supply and Sanitation Systems	High	Moderate	High	High
Education System	Moderate	Moderate	Moderate	Medium
Healthcare System	High	High	Very High	Immediate
Social Welfare Programs	Low	Moderate	Moderate	Medium
Cultural Diversity	Low	Low	Low	Low
Trade and Commerce	High	High	Very High	Immediate
Banking and Financial Institutions	Moderate	Moderate	Moderate	Medium
Labour Market and Employment	High	Moderate	High	High
Industrial and Manufacturing Sectors	High	High	Very High	Immediate
Biodiversity and Ecosystems	High	High	Very High	Immediate
Air and Water Quality	Moderate	Low	Moderate	Medium
Pollution Control and Regulations	Moderate	Moderate	Moderate	Medium
Climate Change Adaptation Strategies	High	High	Very High	Immediate
Government Structure	High	High	Very High	Immediate
Policy and Regulation	Moderate	Moderate	Moderate	Medium
Public Administration and Bureaucracy	High	Moderate	High	High
Law Enforcement and Security Forces	High	High	Very High	Immediate

Interpretation

- **Very high system breakdown risk:** Components with a high criticality to resilience and operational interdependence impact are identified as having the highest risk of causing system breakdowns. Immediate intervention is required to enhance resilience and prevent cascading failures.
- **High system breakdown risk:** Components with either high criticality to resilience and operational interdependence impact are considered high risk. These components should be prioritized for strategic planning and resource allocation to improve system stability.
- **Moderate system breakdown risk:** Components with moderate criticality to resilience and operational interdependence impact show a moderate level of risk. These components require periodic monitoring and intervention when necessary to maintain system resilience.
- **Low system breakdown risk:** Components with low criticality to resilience and operational interdependence impact are at the lowest risk. Although these components are important, they do not require immediate resources for resilience improvements.

Thus, the fundamental elements of seaport infrastructure within the Visakhapatnam Port Authority and Paradip Port Authority ecosystems were identified in this section. This establishes the groundwork for a comprehensive examination of the framework for a systemic risk assessment methodology.





An aerial photograph of a large container ship docked at a port. The ship's deck is filled with numerous stacks of colorful intermodal containers in shades of red, blue, green, and yellow. Two massive blue gantry cranes are positioned over the ship, their long jibs extending outwards. The background shows the deep blue ocean under a clear sky. The title text is overlaid on the upper left portion of the image, next to a solid red rectangular block.

Outcome of the Systemic Risk Assessment Survey

In this section of the analysis, we explore the findings generated from the systemic risk assessment survey, a pivotal component in evaluating systemic risk and resilience within the Visakhapatnam Port Authority and Paradip Port Authority ecosystem. The systemic risk assessment tool, characterized by its multifaceted framework, plays a critical role in dissecting the resilience of the seaport ecosystem across various dimensions. Data collection for the systemic risk assessment tool involves the implementation of a questionnaire survey distributed to key stakeholders. These respondents rate each parameter on a scale ranging from 1 (indicating poor) to 5 (reflecting the best), thereby providing valuable insights into the current and prospective state of resilience within the seaport ecosystem. The quality and reliability of the results hinge on the expertise and knowledge of the respondents. The subsequent analysis of this data can be performed using spreadsheet tools, and the findings can be visualized through spider diagrams, offering a clear and concise representation of the conditions prevailing across different dimensions and domains. To further enhance comprehension, correlation analysis can be employed to establish connections between various aspects of the ecosystem, providing context-based insights that can inform effective solutions.

The foundational structure of this assessment rests on two fundamental viewpoints:

A Intra-system perspective

The intra-system perspective explores the resilience of the ports under consideration by examining the interdependencies and adaptive capacities of their key systems. This approach encompasses a holistic evaluation of resilience across five critical systems: the Physical and Infrastructure System, Economic and Finance System, Ecological and Environmental System, Human, Social, and Cultural System, and Political and Governance System. By assessing these systems, the perspective highlights each port's ability to anticipate, absorb, adapt to, and recover from disturbances. It offers a nuanced understanding of the strengths that enhance resilience and the vulnerabilities that may compromise the port's capacity to withstand and respond to stressors.

B Inter-system perspective

The inter-system perspective addresses the interconnected nature of risk and resilience management, concentrating on systemic risks that transcend individual systems. It evaluates cross-cutting elements such as institutional design and capacity, governance, and system understanding across the five systems within the port ecosystem. These factors are essential for understanding how well a port can navigate and manage complex systemic risks and challenges that may arise from interdependencies among the five systems. This perspective seeks to understand how various systems interact and support each other in enhancing the port's overall resilience.

Both perspectives are examined through a series of carefully crafted questions, which form the basis for a quantitative risk assessment. These questions explore each focal area, facilitating a detailed and comprehensive analysis of the strategies employed for managing systemic risks and enhancing resilience within both the intra-system and inter-system dimensions of the ports.

Key Observations and Analytical Assessments

In the comparative assessment of the Visakhapatnam Port Authority and Paradip Port Authority data, notable variability emerges in their proficiency across both inter-system and intra-system capabilities. The average scores across various categories range from high to moderate to low, showcasing a diverse array of capabilities and preparedness levels. This variation is illustrated in Figure 6. For details on how these results were generated, refer to the guidance notes in Annexure 1 at the end of the document.

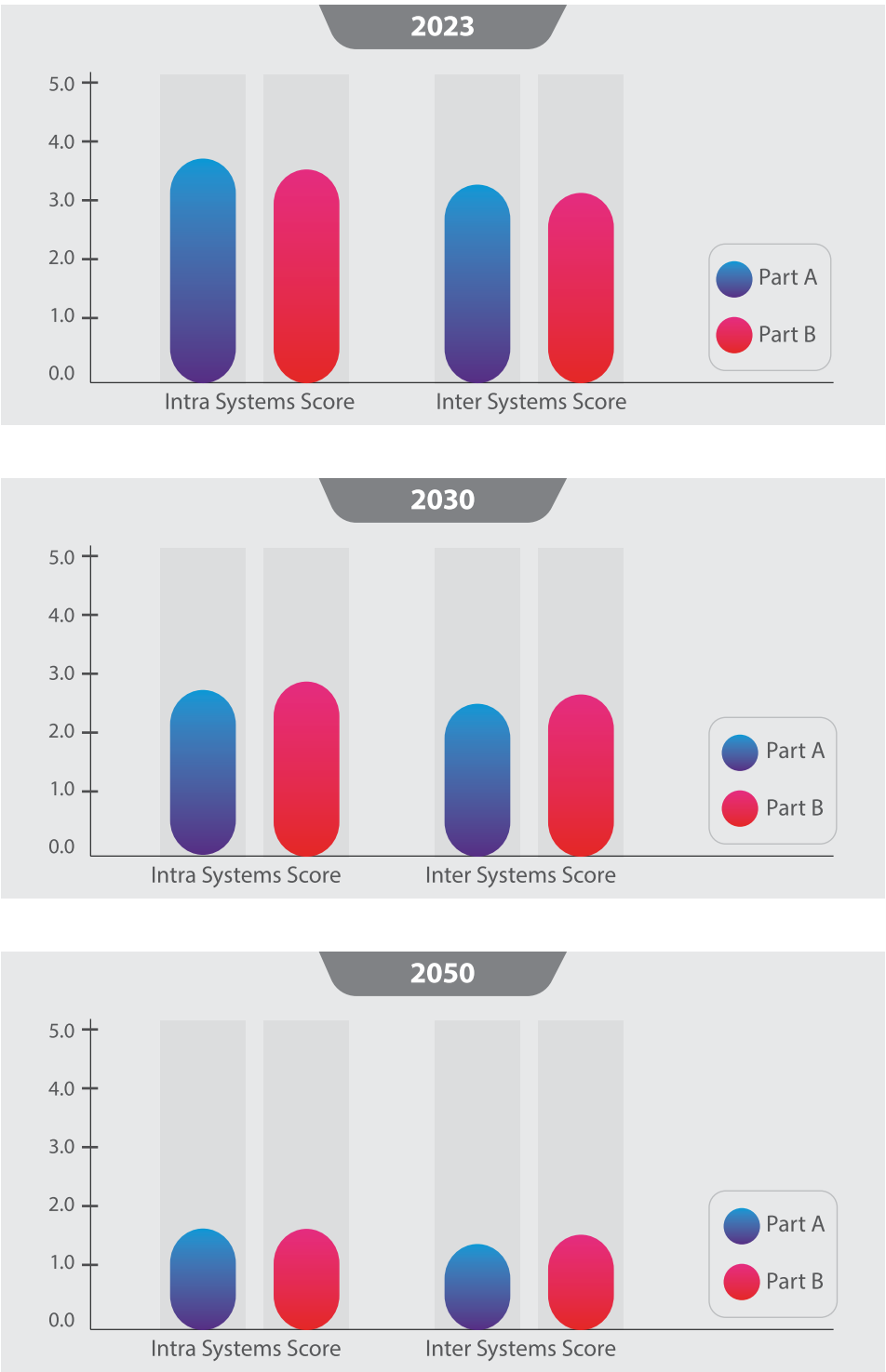


Figure 6: Systemic risk capability assessment score between Paradip Port Authority and Visakhapatnam Port Authority as of 2023, 2030, 2050

The scores reveal that both the Visakhapatnam Port Authority and Paradip Port Authority exhibit comparable levels of preparedness in the present, near, and distant future. However, when considering the extended perspective up to 2050, the systemic risk capabilities of both Visakhapatnam Port Authority and Paradip Port Authority exhibit a substantial decline. This decline reflects the difficulties each port faces in sustaining long-term resilience and managing risks effectively. The summary of readiness at both intra and inter-system levels can be further substantiated by the underlying data by domains for both Visakhapatnam Port Authority and Paradip Port Authority, which show a similar trend to the overall scores depicted in Figure 7.

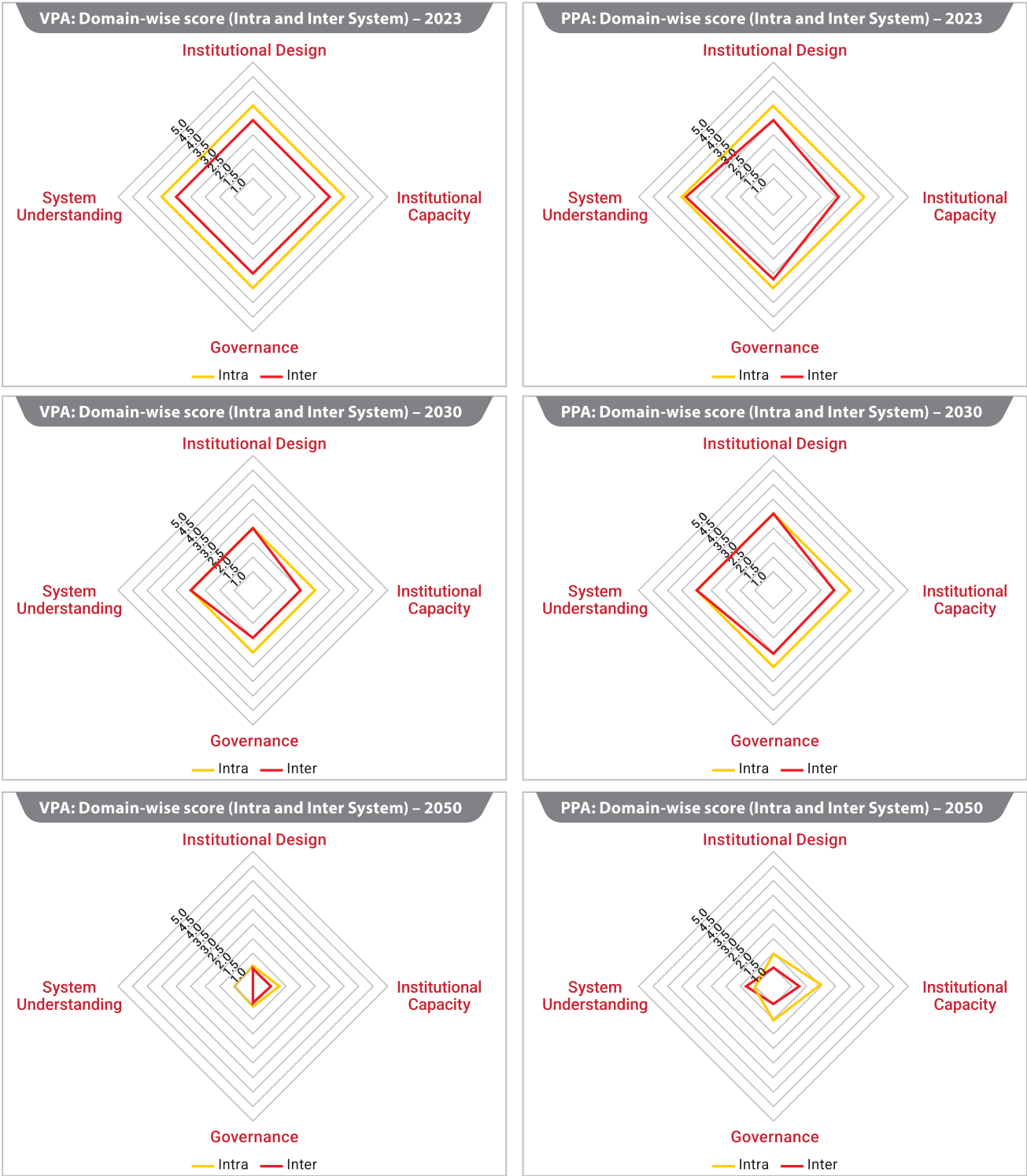


Figure 7: Domain-wise inter- and intra-system scores for the Visakhapatnam Port Authority and Paradip Port Authority for 2023, 2030, 2050

Qualitative Insights Emerging from the Inter Systems Scores: By Domain

In examining the domain-wise scores of the inter-systems scores within the Visakhapatnam Port Authority and Paradip Port Authority ecosystems, several significant findings have emerged. This analysis delves into these findings to shed light on the existing strengths and areas that require attention within these domains. Refer to Figure 8 and Table 9.

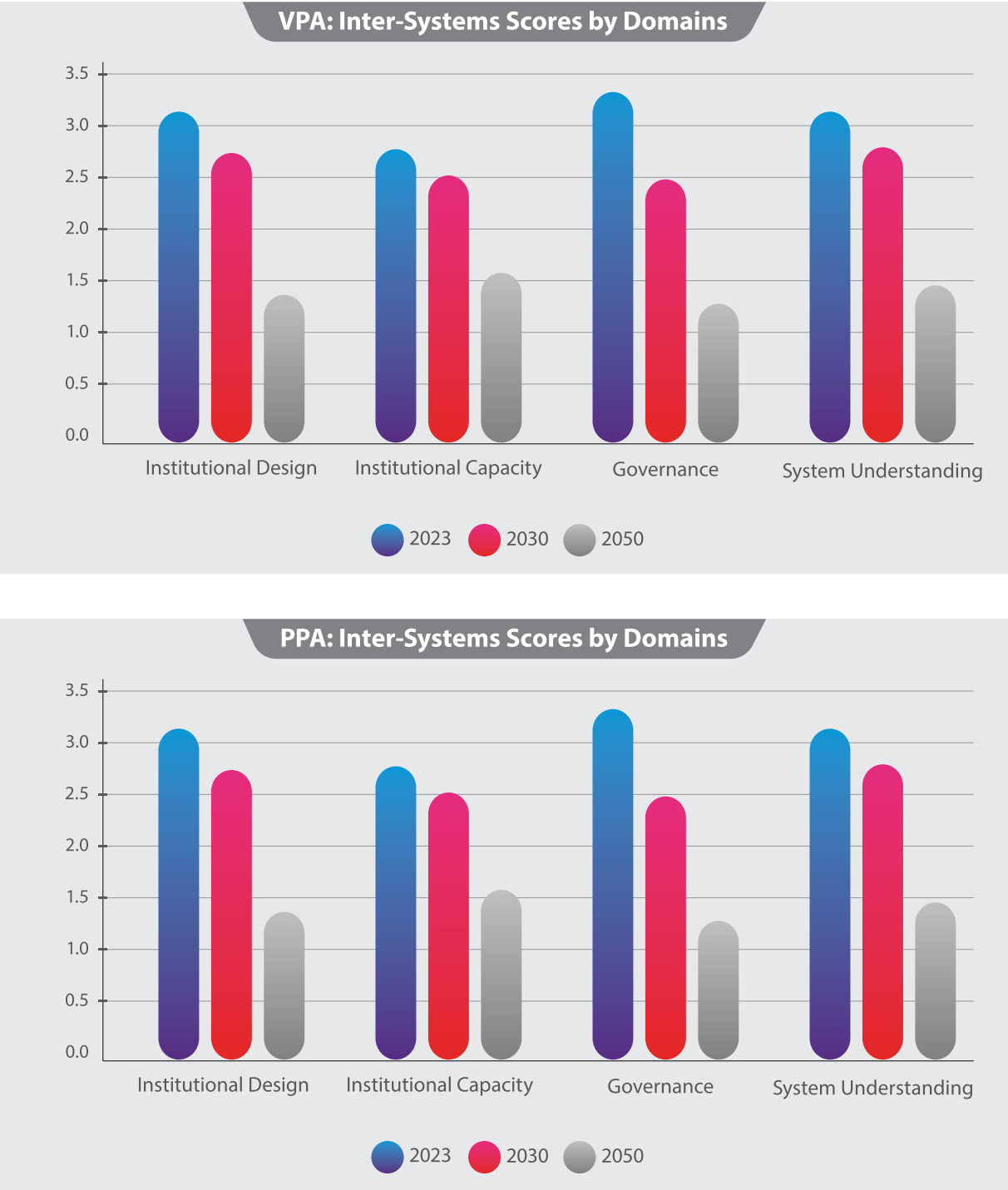


Figure 8: Domain-wise break up of inter-system score for the Visakhapatnam Port Authority and Paradip Port Authority for 2023, 2030, and 2050

Table 9: Key insights from an institutional design perspective (inter-system)

Aspect	Short Term	Long Term
Vision and Common Charter	Both Visakhapatnam Port Authority and Paradip Port Authority have made significant strides in establishing a unified vision and charter for disaster risk management. This includes comprehensive plans covering equipment, mitigation, public warning, preparedness, response, recovery, and capacity building. These efforts have improved coordination and effectiveness in addressing immediate risks.	However, the absence of a cohesive framework for long-term systemic risk management poses challenges in sustaining effective disaster risk management of chronic issues and maintaining resilience as climate risks evolve.
Coherent Policies and Regulations	Comprehensive policies and regulations have been successfully implemented, supporting disaster risk management for specific hazards.	There is a critical need for more coherent policies that promote sustainable port resilience. This requires adopting a forward-looking strategy integrating future projections into all systems to facilitate anticipatory and proactive measures for multi-hazard mitigation and addressing systemic risk.
Integration of Affected People's Perspectives	Current initiatives are making strides in integrating the perspectives of affected communities into disaster response efforts, fostering inclusivity and responsiveness.	As extreme weather events increase in intensity, long-term impact and vulnerabilities grow, particularly as populations migrate to low-lying and sensitive areas. It is essential to mainstream the voices of the local communities into broader urban planning and disaster risk management initiatives.
Budgets/Funds Availability	Adequate budgets are allocated for disaster risk management in the short and long term, focusing primarily on immediate disaster management needs.	There is currently no specific allocation of resources for climate adaptation initiatives to effectively address systemic risks in the long term.
Mainstreaming of Systemic Risk Management	There is moderate to limited mainstreaming of systemic risk management principles in development and planning efforts, resulting in only partial impact.	More concerted efforts are needed to fully integrate systemic risk management principles into core design and planning strategies, which are essential for enhancing overall resilience and effectiveness.



Key Insights from an Institutional Capacity Perspective (Inter)

Assessing institutional capacity within the context of systemic risk management in seaport ecosystems yields valuable insights into the readiness and effectiveness of both the Visakhapatnam Port Authority and Paradip Port Authority ecosystems. Refer to Table 10.

Table 10: Key insights from an institutional capacity perspective (Inter)

Aspect	Short Term	Long Term
Incorporation of Multi-Hazard Risk Assessment	Currently, both Visakhapatnam Port Authority and Paradip Port Authority primarily prioritize single hazard risk assessment with actions primarily tailored to address immediate threats.	Limited to no incorporation of multi-hazard risk assessment in the long term, indicating vulnerability to unforeseen challenges and underscoring the need for sustained commitment to comprehensive risk assessment and planning.
Established Protocols for Coordination	Significant progress in establishing protocols for coordination and restoration efforts in the short term, leading to streamlined response mechanisms and efficient inter-agency coordination.	Protocols for coordination and restoration efforts primarily address immediate hazard occurrences, neglecting long-term impacts and future projections. This suggests the necessity of maintaining and regularly updating coordination procedures to sustain effective long-term resilience.
Awareness Levels on Systemic Risk Management	Substantial awareness of systemic risk management among stakeholders in the short term, contributing to positive impacts on systemic risk management initiatives.	There is a concerning shift towards limited to no awareness among port authorities and stakeholders regarding the future of unknown risk associated with the increasing intensity of cyclonic events or extreme weather events.
Effectiveness of Proactive Capacity Building	Moderate effectiveness of proactive capacity building across the ecosystem in the short term.	Proactive capacity building is likely to become ineffective over time in managing the systemic risk portfolio without long-term planning. It needs to improve ongoing and adaptive efforts to maintain readiness in managing systemic risk portfolios.
Existence of Technology and Data Support	Substantial evidence of technology, data, and advanced technologies supporting systemic resilience in the short term, significantly enhancing response and recovery capabilities.	Most of the existing technologies and data do not effectively support systemic risk management for future scenarios. It suggests potential regression in technological capabilities and highlights the need for continued investment and innovation in this area to maintain effective response and recovery capabilities.

Key Takeaways from a Governance Perspective (Inter)

The governance perspective within the context of systemic risk management in seaport ecosystems of the Visakhapatnam Port Authority and Paradip Port Authority offers crucial insights into the collaborative efforts and mechanisms in place to address systemic risks effectively. Refer to Table 11.

Table 11: Key takeaways from a governance perspective (inter)

Aspect	Short Term	Long Term
Existence of Multi-Stakeholder Platforms	There is a moderate existence of multi-stakeholder platforms for risk management involving key stakeholders such as the port authority, governments at various levels, markets, civil society, and the community, but their impact remains partial.	The existence of multi-stakeholder coordination could undermine long-term systemic risk management due to the emergence of public-private partnership models at seaports. This is because of conflicts of interest, unequal private sector influence, loss of public control, and the risk of essential service or infrastructure privatization.
Effectiveness of Transboundary Governance	In the short term, multi-stakeholder platforms for disaster risk management show moderate effectiveness in transboundary governance but only have a partial impact on facilitating coordinated efforts among diverse stakeholders.	The long-term effectiveness of coordination through multi-stakeholder platforms for disaster risk management may diminish, as it may not adequately address the complexities of long-term risks in transboundary governance.
Mechanisms for Transparency and Accountability	There are substantial mechanisms in place to ensure transparency and accountability in the port's risk management practices. These mechanisms have a significant impact on promoting openness and responsible conduct.	Mechanisms are not fully developed in the long term. An adequate sense of accountability exists.

Key Takeaways from System Understanding Perspective (Inter)

Analysing system understanding within the context of systemic risk management in seaport ecosystems provides valuable insights into the depth of comprehension and readiness to address systemic risks. Refer to Table 12.

Table 12: Key takeaways from system understanding perspective (inter)

Aspect	Short Term	Long Term
Subsystem Identification and Relationship Mapping	There is an adequate level of mapping 'within' systems, with subsystems identified and clear relationships established among components. This signifies a commendable effort in comprehending the internal dynamics of most systems.	In the long term, while sub-system identification stays consistent, however, relationship mapping is likely to change as new risks emerge, posing concerns for long-term resilience.
System Boundaries, Stakeholders, and Relationship Mapping	There is substantial mapping 'between' inter-systems, with a clear establishment of system boundaries, stakeholders, and relationships. This demonstrates a promising effort to delineate external influences on these systems.	Limited delineation of system boundaries, stakeholders, and relationship mapping implies a lack of preparedness for addressing cross-system influences.
Transboundary Effects Mapping	There is limited mapping of transboundary effects in the short term. There is a notable gap in understanding the potential contagion and spillover effects within and between inter-systems.	There is still limited to no mapping of transboundary effects. This persistent gap underscores the importance of comprehending the intricate web of influences that can propagate across systems, posing significant challenges to systemic resilience.
Pre-identified Outcomes/Impact Areas from System Failures	Pre-identifying outcomes and impact areas resulting from inter-system failures are limited in the short term. The understanding of the potential consequences of such failures is not comprehensive.	In the long term, this limitation persists, with limited to no mapping of outcomes and impact areas.

In the short term, a strong positive correlation is observed between the establishment of a clear vision and common charter for systemic risk management and the coherence of policies and regulations. Additionally, there is a positive correlation between integrating affected people’s perspectives and mainstreaming systemic risk management, as well as between the availability of budgets and funds and the mainstreaming of these practices. However, as we extend our analysis to the long term, these correlations weaken, indicating challenges in maintaining alignment between the vision and policies, sustaining the integration of affected perspectives, and ensuring consistent policies and regulations. Despite this weakening, the positive correlation between budget availability and mainstreaming remains consistent over time, although this connection is restricted to disaster risk management. Furthermore, positive correlations are observed between the incorporation of multi-hazard risk assessments and the awareness of systemic risk management, as well as between transparency/accountability mechanisms and the existence of multi-stakeholder platforms, both in the short and long terms. These findings underscore the evolving nature of systemic risk management dynamics and emphasize the importance of sustained efforts and attention to various aspects to enhance systemic resilience in seaport ecosystems over time.

Qualitative Insights Emerging from the Intra-Systems Scores: By System

Upon closer examination of the system-level readiness (see Figure 9), which forms a critical component of the intra-system readiness levels, each system’s readiness shows variability within the Visakhapatnam Port Authority and Paradip Port Authority. Over the short, medium, and long term, the overall intra-system readiness scores are declining.

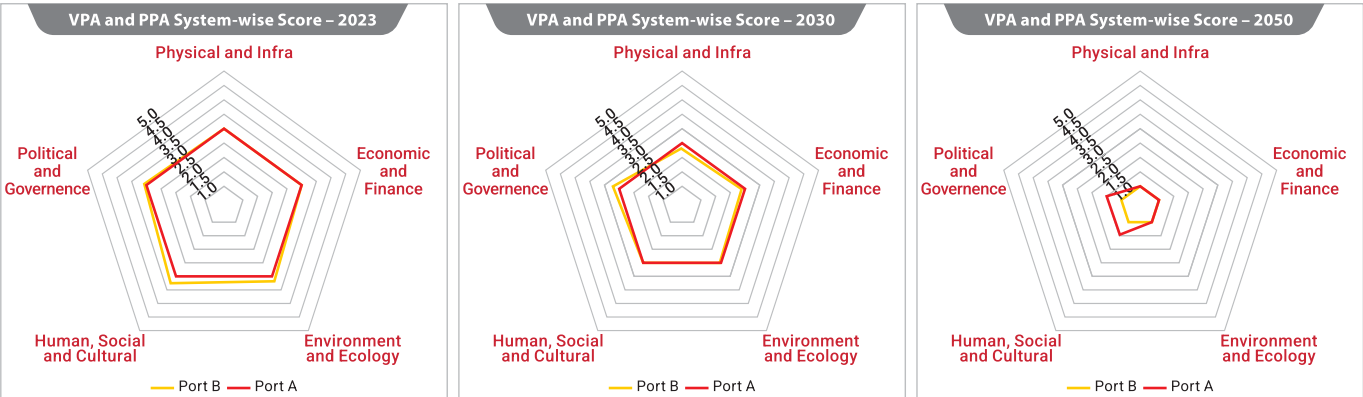


Figure 9: System-wise scores for Paradip Port Authority and Visakhapatnam Port Authority

(a) Physical and Infrastructure System

Examining physical and infrastructure systems within the context of systemic risk management in the Visakhapatnam Port Authority and Paradip Port Authority provides crucial insights into the foundational aspects of resilience. This analysis scrutinizes various facets of the systems, shedding light on their current status and long-term prospects.

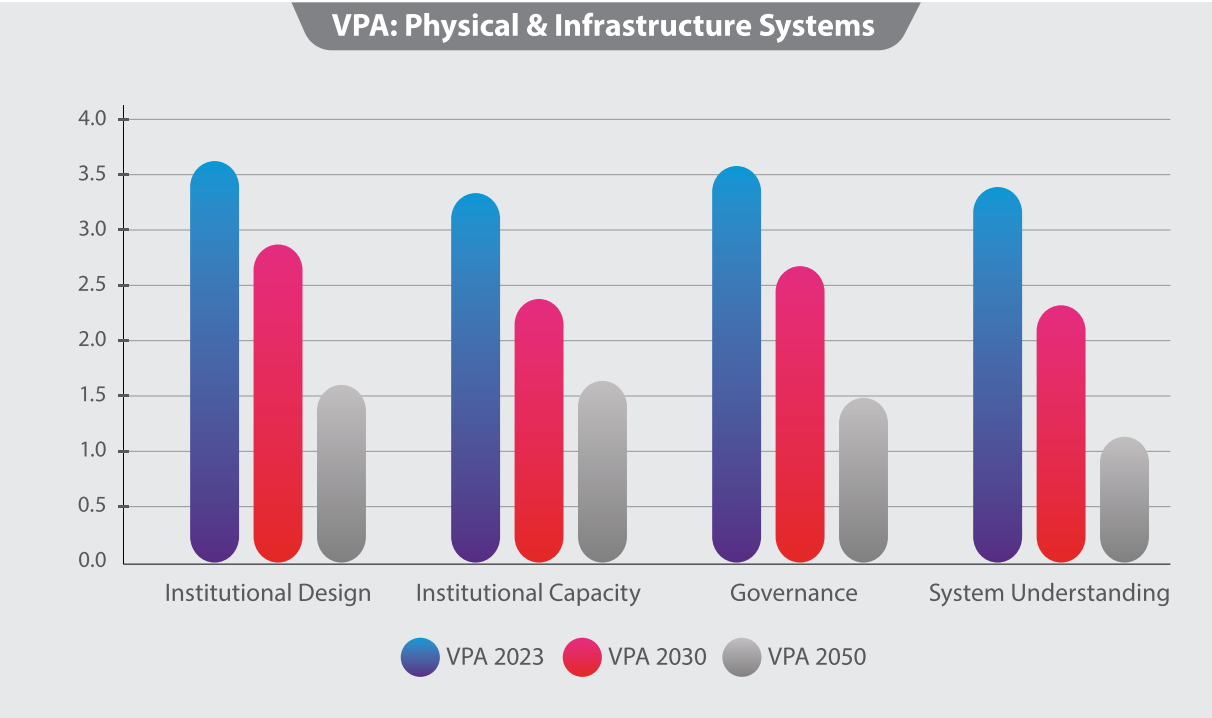
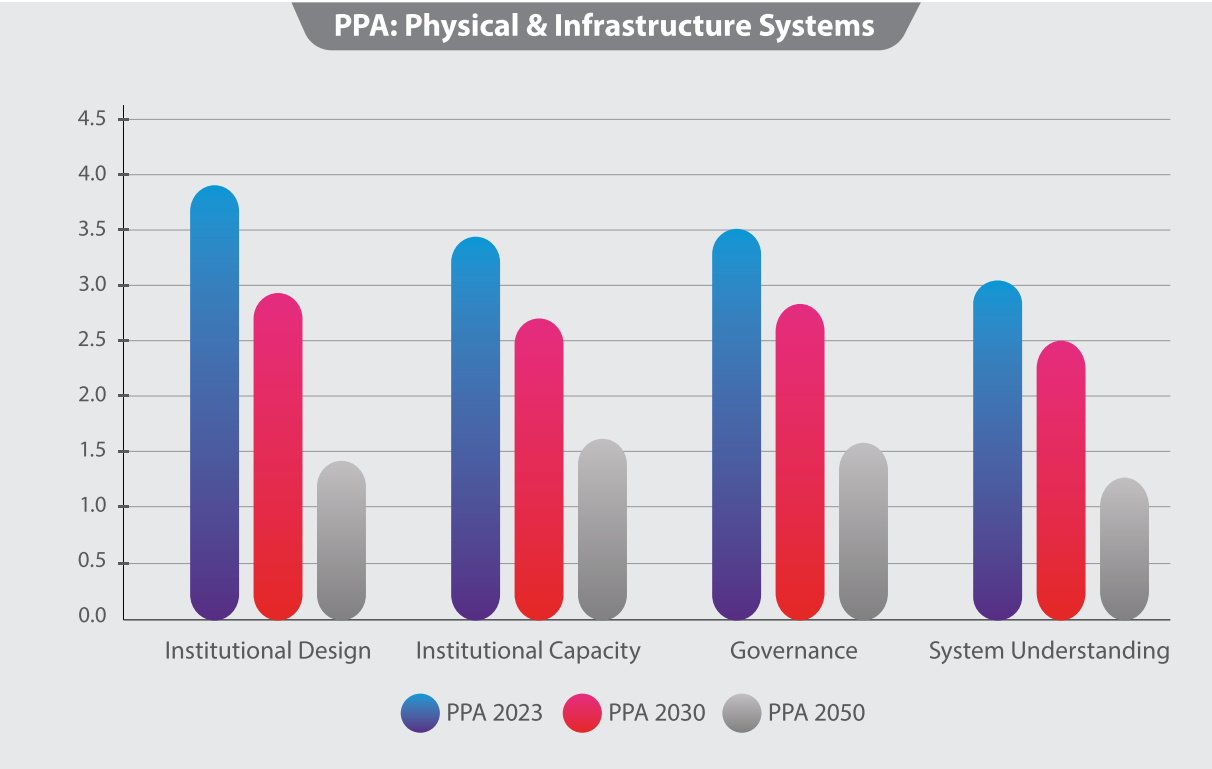


Figure 10: Physical and infrastructure systems analysis in the Visakhapatnam Port Authority and Paradip Port Authority

Figure 10 provides a concise overview of the key insights from each perspective in examining physical and infrastructure systems in the context of systemic risk management in the Visakhapatnam Port Authority and Paradip Port Authority ecosystems.

(b) Economic and Financial Systems

Figure 11 provides a concise overview of the key insights from each perspective in examining Economic and Financial Systems in the context of systemic risk management in Visakhapatnam Port Authority and Paradip Port Authority ecosystems.

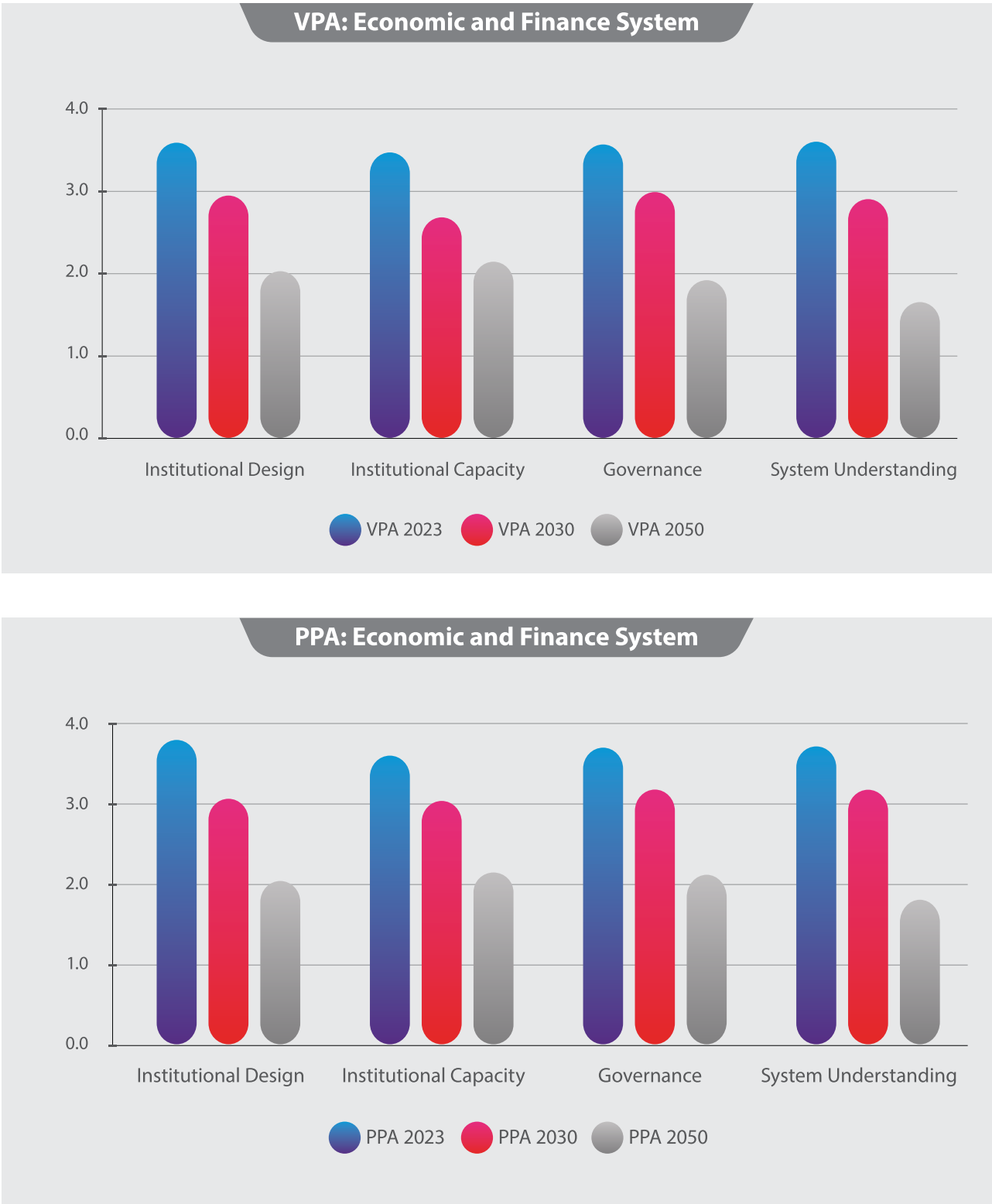


Figure 11: Economic and financial systems analysis in the Visakhapatnam Port Authority and Paradip Port Authority

(c) Ecological and Environmental System

Figure 12 provides a concise overview of the key insights from each perspective in examining the ecological and environmental systems in the context of systemic risk management within Visakhapatnam Port Authority and Paradip Port Authority ecosystems.

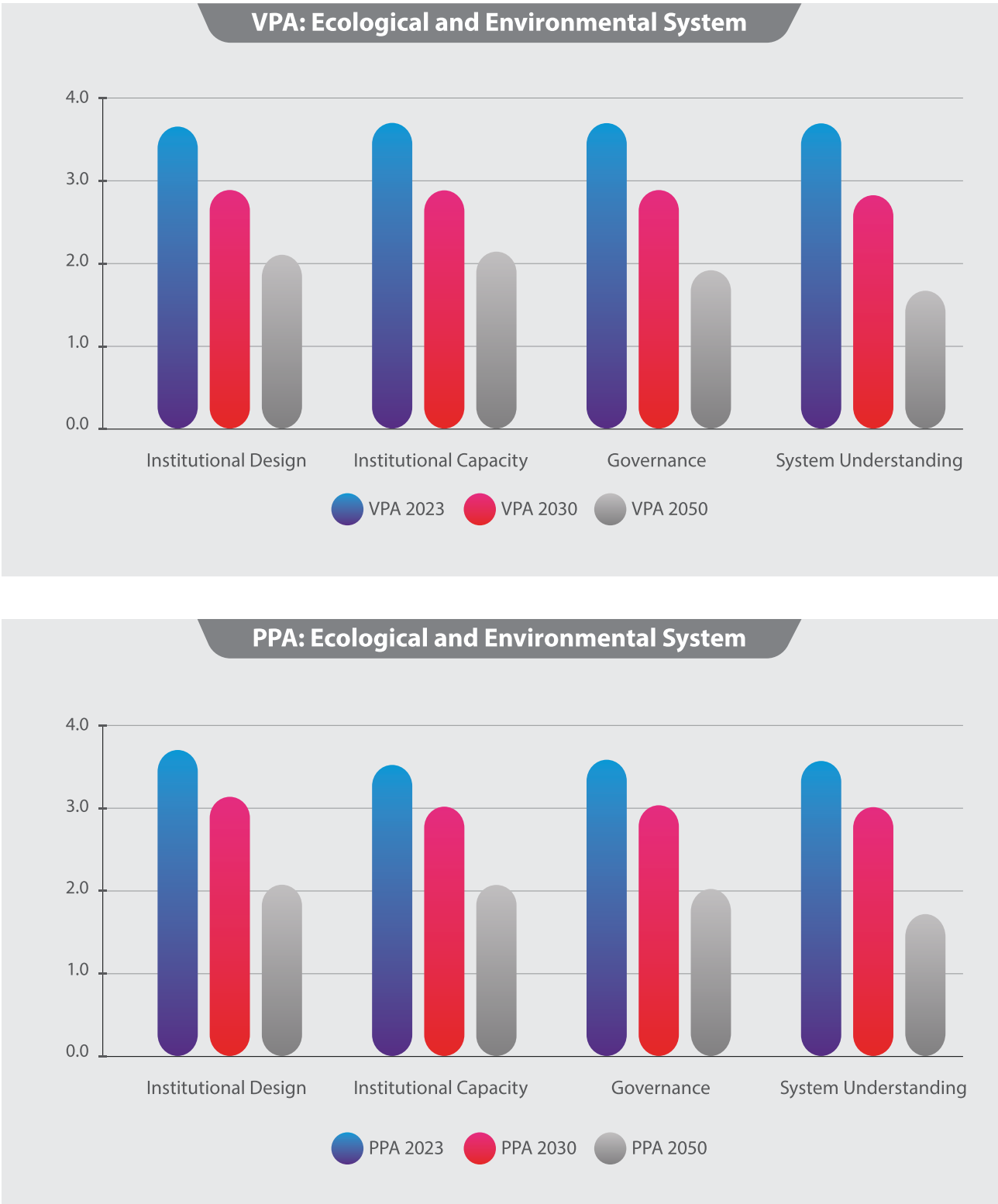


Figure 12: Ecological and environmental systems analysis in the Visakhapatnam Port Authority and Paradip Port Authority

(d) Human, Social, and Cultural System Analysis

Refer to Figure 13.

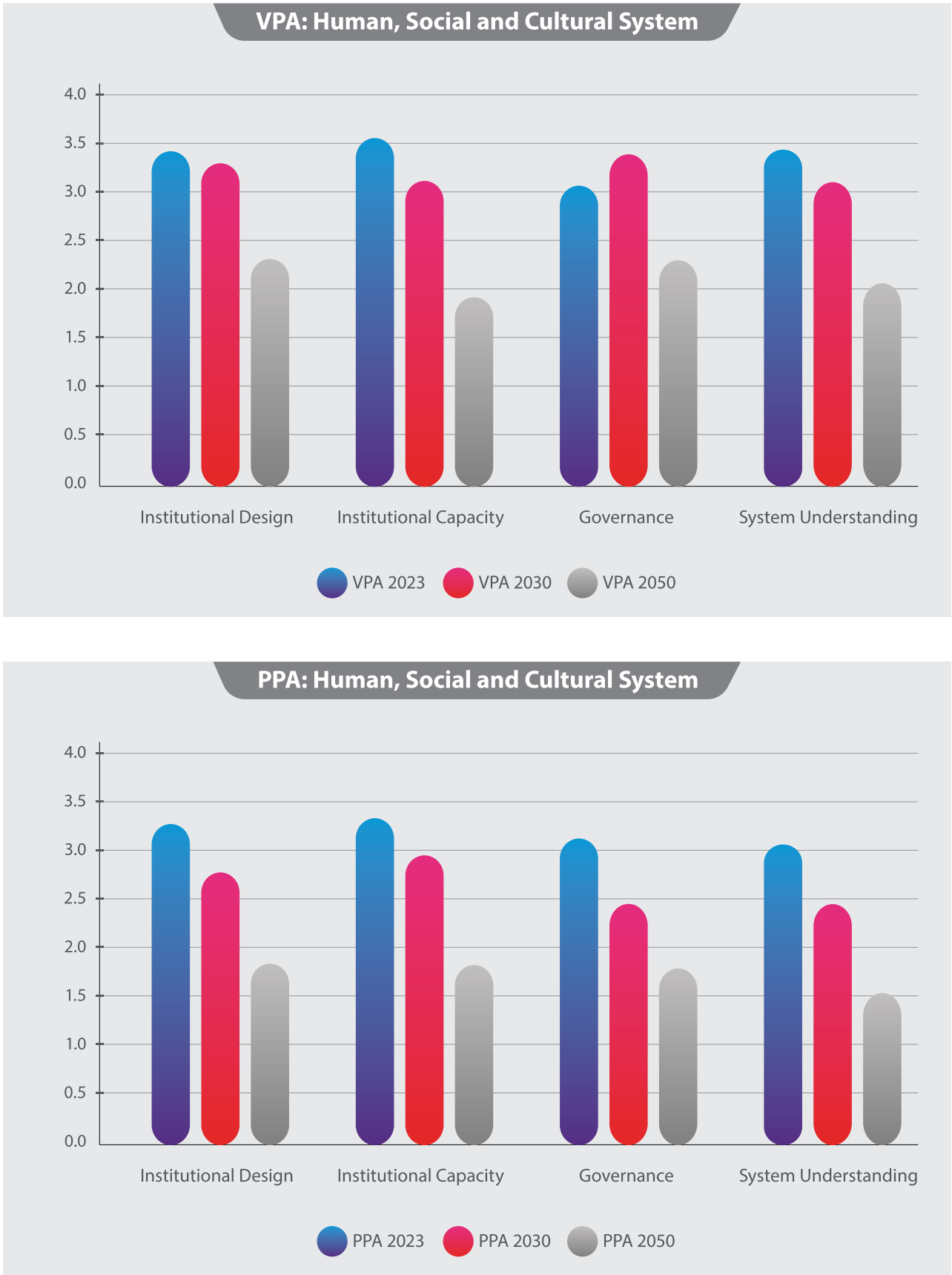


Figure 13: Human, social, and cultural system analysis in Visakhapatnam Port Authority and Paradip Port Authority

(e) Political and Governance System Analysis (Connect with State)

Refer to Figure 14.

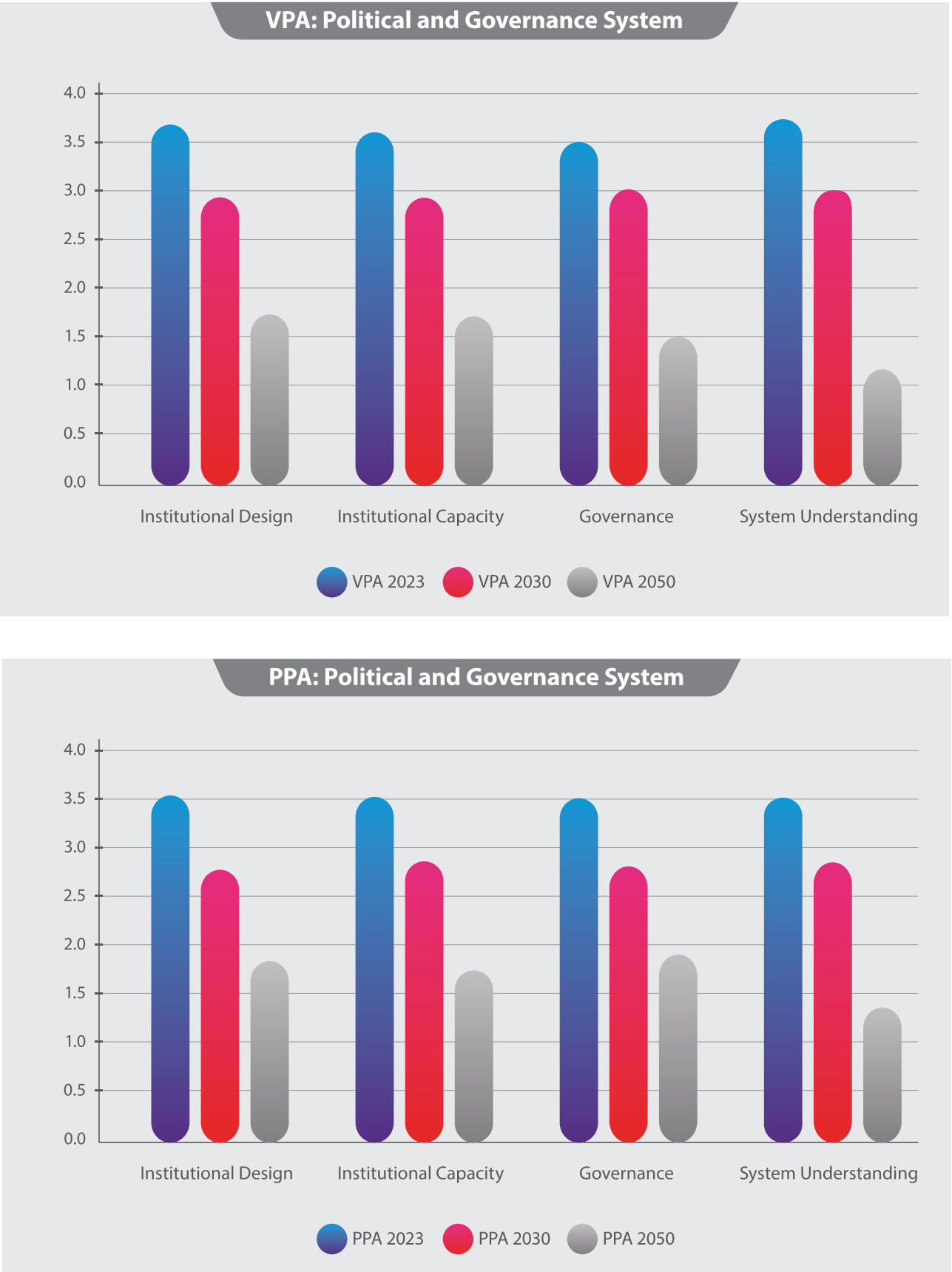


Figure 14: Political and governance system analysis in Visakhapatnam Port Authority and Paradip Port Authority

Examining the vulnerabilities of the Visakhapatnam Port Authority and Paradip Port Authority from a qualitative lens reveals intricate interdependencies within their physical and social infrastructures. This emphasizes the need for a nuanced understanding of their resilience to disasters. Both ports face significant challenges due to recurring cyclones and storm surges, which expose critical weaknesses in their operational frameworks and threaten their long-term sustainability.

Visakhapatnam Port Authority



Visakhapatnam Port Authority, as one of India's oldest ports, is emblematic of the challenges posed by ageing infrastructure. Historic events, such as the 2004 Indian Ocean Tsunami and Cyclone Hudhud in 2014, have starkly illustrated the port's vulnerability. The extensive damage inflicted during Cyclone Hudhud revealed not only the port's physical fragility—especially concerning its breakwaters and jetties—but also the operational risks that arise from such deterioration. The nearly year-long repair process that followed these incidents underscores how deeply interconnected Visakhapatnam Port Authority's operational capability is with the integrity of its infrastructure.

Moreover, the port's location within the urban fabric of Visakhapatnam creates a complex web of systemic risks. While integrating the Visakhapatnam Port Authority with the city's roads, railways, and cargo storage systems enhances its logistical efficiency, it simultaneously heightens its exposure to climatic threats. Cyclone Hudhud's impact on the port reverberated throughout the city, disrupting businesses and prompting some to reconsider their future in the area. This retreat reflects a broader concern regarding urban resilience in the face of climate change, indicating that Visakhapatnam Port Authority's vulnerabilities extend beyond its physical structures to include economic and social dimensions.

Paradip Port Authority

Paradip Port Authority's journey towards enhanced disaster preparedness, especially since the catastrophic 1999 Odisha Super Cyclone, highlights both progress and persisting vulnerabilities. Cyclone Amphan in 2020 had substantial impacts, affecting over 18 million people and resulting in damages surpassing INR 1 trillion —highlighting the ongoing challenges Paradip Port Authority faces. While improvements in evacuation procedures and relief efforts have been made, the port and surrounding areas remain susceptible to frequent cyclones, as well as additional threats such as flash floods and waterlogging during the monsoon.

The devastating impacts on local infrastructure, including extensive damage to roads and power systems, further illustrate the interlinked nature of physical and socio-economic resilience. The widespread destruction of homes and the detrimental effects on agriculture and fisheries reveal a multifaceted vulnerability that extends well beyond the immediate aftermath of a cyclone, potentially altering community dynamics and local economies for years to come.



Economic Performance Amid Vulnerabilities

Despite these vulnerabilities, both Visakhapatnam Port Authority and Paradip Port Authority are performing exceptionally well in India's economic landscape. In the fiscal year 2019/2020, they handled impressive cargo volumes—Paradip Port Authority at 112.69 million tonnes and Visakhapatnam Port Authority at 72.72 million tonnes—demonstrating their critical roles in national logistics and revenue generation. However, the rising frequency of extreme weather events brings to the fore the urgent need for resilience measures. The increasing costs associated with environmental disruptions, along with investments in disaster impact insurance, highlight the precarious balance these ports must navigate between operational efficiency and environmental risk.

Ecological and Social Resilience

The long-term effects of climate change are evident in various ecological and social dimensions. Issues such as salinization, coastal erosion, and the accumulation of marine debris not only threaten infrastructure but also endanger the health of ecosystems and the livelihoods that depend on them. The ecological recovery of damaged areas, like mangroves, can take several years. During this time, the connection between environmental health and community well-being becomes clear. Vulnerable populations facing health impacts may face compounded challenges, affecting family stability and children's education, ultimately perpetuating cycles of poverty and vulnerability.



Discussion and Findings on Inter-System and Intra-System Readiness

The systemic risk management framework within the environments of Visakhapatnam Port Authority and Paradip Port Authority illustrates an intricate network of interdependencies across physical, economic, environmental, and governance domains.

This assessment aims to provide a comprehensive analysis of the structural, operational, and strategic readiness of both ports in managing existing and emerging risks. Evaluating inter- and intra-system readiness highlights the strengths, challenges, and opportunities in disaster risk management, emphasizing the importance of enhancing resilience and adaptability.



The strategic analysis of the seaport ecosystems of Visakhapatnam Port Authority and Paradip Port Authority reveals a nuanced portrait of preparedness that intersects multiple systemic dimensions. Presently, both ports demonstrate robust disaster risk management capabilities, founded on a shared vision and operational coherence, as evidenced by their disaster management strategies and institutional frameworks. Despite having well-developed disaster risk management systems, it is noteworthy that neither ports explicitly incorporate the concept of systemic risk in their documentation; their guidelines primarily address risk management in isolation rather than from a systemic perspective. Furthermore, resource allocation predominantly favours climate mitigation initiatives, such as environmental management within ports and achieving energy self-reliance through solar installations and water treatment measures. This shift indicates a move away from adaptation and resilience-building measures, which are essential for upgrading and retrofitting existing infrastructures to withstand severe cyclonic storms and heavy flooding, as well as for investing in ecosystem-based solutions.

Effective public-private partnerships and contingency plans bolster physical infrastructure, contributing to short-term operational stability. The economic frameworks remain solid, providing a stable financial backdrop for systemic risk management. While established early warning systems and evacuation plans emphasize human safety and infrastructure, they fall short in addressing the ecosystem and cultural aspects vital for a systemic risk approach and resilience building. There is a lack of information regarding how existing infrastructure is being adapted to withstand climate change impacts, suggesting insufficient emphasis on retrofitting or fortifying current facilities against climatic threats. Furthermore, the absence of data on adaptation measures incorporated into new infrastructure projects reflects a potential gap in ensuring that future facilities can withstand changing environmental conditions.



The limited availability of data on social-related operational challenges, such as labour strikes, highlights a gap in understanding the social factors that can impact port operations and their preparedness to manage these disruptions. The absence of measures to mitigate social-related disruptions suggests that strategies for addressing labour or social unrest may not be fully developed within the operational frameworks of ports. Overall, the findings reveal substantial gaps in future-proofing strategies across various dimensions, particularly in areas such as flexible planning, climate adaptation, human capital development, and preparedness against sudden disruptions.

However, projecting these findings into the future, specifically towards 2050, reveals an observable downward trajectory in overall systemic readiness. This trend underscores the challenges of sustaining long-term resilience and effectively managing risks. This trend points to the inherent difficulties in maintaining momentum and updating systemic risk management efforts in response to evolving systemic pressures over extended timeframes. The absence of a comprehensive long-term vision and charter, combined with a decline in the effectiveness of transboundary governance through multi-stakeholder platforms, presents significant challenges to the system's ability to govern and manage risks effectively. This highlights the need for a more holistic approach that considers systemic risks and fosters transboundary collaboration to address cascading risks effectively.

Future Scenarios and Implications

This analysis elucidates the intricate interdependencies within the seaport ecosystem's systems and components, emphasizing their collective influence on long-term resilience. While the current state of readiness is adequate for present and near-future scenarios, there are concerns about how well this interconnected web can withstand more severe future stressors. This underscores the need for a holistic and adaptive systemic risk management approach that not only fortifies individual systems but also enhances the agility and synergy between them.

To substantiate these insights, three distinct future scenarios have been envisaged, each escalating in impact and providing a temporal lens to evaluate systemic readiness and response strategies:

1. Scenario 1 (2023):

Mild impacts are anticipated from current levels of climate change and cyclonic events, which are manageable for Visakhapatnam Port Authority and Paradip Port Authority. The existing infrastructure and policies are deemed sufficient, suggesting a positive short-term outlook. However, inter-system coordination, while adequate, is not optimized for peak performance. This indicates areas for improvement in integrated preparedness strategies.

2. Scenario 2 (2030):

There is a moderate predicted increase in the intensity and frequency of coastal hazards. Here, the pace of adaptation and systemic evolution appears misaligned with the accelerating risk landscape. While some

initial adaptations have been noted, the delay in inter-system preparedness highlights a critical gap in collective response capabilities, underscoring the urgency for more concerted efforts to enhance both horizontal and vertical coordination and foster robust response strategies.

3. Scenario 3 (2050):

The situation envisions severe impacts from escalated coastal hazards. The SRM framework, at both intra- and inter-system levels, appears inadequate in confronting the severity of these impacts. This scenario serves as a stark reminder for a paradigm shift towards more comprehensive and forward-thinking measures to fortify the seaport ecosystems against impending high-intensity challenges.

These scenarios collectively form a trajectory that, while starting from a position of strength, progressively diverges toward vulnerability. They accentuate the necessity for a dynamic and integrated systemic risk management approach capable of pivoting in real time to emerging risks and maintaining the integrity of the seaport ecosystems in the face of a changing risk landscape. It is crucial to have systemic agility, enhanced by continuous learning and adaptation, to ensure that the seaport ecosystems of Visakhapatnam Port Authority and Paradip Port Authority not only withstand the test of time but also serve as models of resilience in the maritime domain.

In conclusion, resilience must be anticipatory, adaptable, and aligned with the complex web of interconnections that define the very fabric of these port ecosystems. By bridging the identified gaps and harnessing existing strengths, the seaport ecosystems can aspire not only to navigate but also thrive amidst the systemic flux of the future.



A large cargo ship is seen from behind, sailing on a deep blue ocean under a bright blue sky with scattered white clouds. A long, straight path of stacked shipping containers leads from the bottom of the frame towards the ship's stern. The containers are in various colors, including red, blue, yellow, and brown, and show signs of wear and rust. The ship's white superstructure and mast are visible in the distance. The water around the ship is turbulent, with white foam from the wake.

Way ahead

A Holistic Approach to Resilience

Addressing these multifaceted vulnerabilities requires a comprehensive and holistic approach to resilience that transcends immediate response strategies. Building interconnected systems that prioritize community preparedness and resilient infrastructure is essential. This approach necessitates active involvement from local communities to improve their preparedness and resilience, fostering a sense of ownership and engagement that is crucial in times of crisis.

Governance and Strategic Frameworks

Although both ports demonstrate strong disaster risk management and coordination in peacetime, challenges often emerge during actual disasters. These inconsistencies highlight the need for robust governance frameworks prioritizing adaptability and responsiveness. Strengthening these mechanisms and implementing proactive measures will be vital for effectively addressing unforeseen risks and bolstering overall resilience.

By enhancing governance structures, mainstreaming adaptation measures, and adopting a systemic risk management approach, the Visakhapatnam Port Authority and Paradip Port Authority can better navigate the complexities of resilience in an increasingly unpredictable climate. This comprehensive strategy will fortify their defences against environmental hazards and ensure the continuity of their vital economic contributions to India's maritime infrastructure. Ultimately, fostering resilience is not just about mitigating risks; it entails cultivating a robust, interconnected community capable of thriving in the face of adversity.

Strategic Recommendations

Integrating systemic risk management into all developmental processes and adapting to evolving environmental and climatic challenges could improve long-term resilience. Strengthening initiatives focused on biodiversity, such as coastal restoration, will provide greater ecological stability. Addressing social and cultural dimensions within systemic risk management would foster community resilience while refining governance frameworks can enhance coordination and coherence in risk management policies.

Global Best Practices

In this section, we explore various adaptation measures adopted by ports globally, offering additional insights for enhancing seaport resilience in the face of systemic risks. Some of the key measures have been highlighted below.

(a) Port and City Integration in Climate Change Adaptation Measures

Recognizing ports as vital nodes in global maritime commerce and transportation, this policy should address challenges and opportunities presented by climate change to ensure a sustainable relationship between ports and their urban surroundings. Therefore, it is essential to integrate climate change adaptation measures between port authorities and their respective cities to foster resilience. This is exemplified by initiatives undertaken in major port cities like Rotterdam, where the port and city have initiated the 'Rotterdam Climate Proof programme'.

This collaborative initiative involves a range of measures to enhance climate resilience, such as raising the storm surge barrier, creating additional water storage capacity, developing floating and adaptive buildings, enhancing urban green infrastructure, and promoting renewable energy and circular economy practices. The Rotterdam Climate Proof programme exemplifies a holistic and long-term approach to climate change adaptation, highlighting the importance of collaborative efforts between city and port authorities to effectively address climate risks.

Similarly, Singapore, being a small island nation heavily reliant on trade, faces unique challenges related to climate change, including sea-level rise and changing weather patterns. To mitigate these risks and promote sustainability, the city and its port have adopted the Singapore Green Plan 2030. This comprehensive plan outlines various measures aimed at enhancing environmental sustainability and resilience. Key initiatives include strengthening coastal protection, improving water supply and efficiency, enhancing energy efficiency and diversification, promoting urban cooling and biodiversity, and fostering green innovation and collaboration. Each city has adopted tailored approaches to address its specific challenges, highlighting the importance of collaborative efforts between city and port authorities and integrating port activities with broader environmental and social goals.

(b) Green-Blue-Grey Solution

Investing in green and blue infrastructure, along with nature-based solutions, is essential for enhancing climate resilience and improving ecosystem health. Coastal restoration, mangrove conservation, and green/blue space development along the port-city interface offer climate adaptation benefits and co-benefits such as improved water quality and increased biodiversity. Since the Industrial Revolution, built infrastructure has primarily overlooked the protection of natural ecosystems. Infrastructure managers have typically failed to account for environmental damage when designing, operating, maintaining, and managing asset networks. Assessment management practitioners are pivotal in maximizing asset value by harnessing the benefits of healthy ecosystems. As urban populations grow and infrastructure networks become increasingly critical, addressing past mistakes and embracing nature-based solutions is imperative. Estimates suggest that nature-based solutions could account for up to 37 per cent of the mitigation needed to address climate change.²⁵ For example, the Resilient Norfolk Coastal Storm Risk Management (CSRM) Project incorporates living shorelines such as oyster reefs and wetlands to absorb wave energy and storms, reduce erosion, and support marine life habitat. This holistic approach, combined with collaboration and community engagement, generates multiple benefits, including increased resilience, economic vitality, environmental sustainability, and social equity.²⁶

²⁵ World Bank. (n.d.). What You Need to Know About Nature-Based Solutions to Climate Change. Retrieved from <https://www.worldbank.org/en/news/-feature/2022/05/19/what-you-need-to-know-about-nature-based-solutions-to-climate-change>

²⁶ International Coalition for Sustainable Infrastructure. (2023). The Climate Resilient Infrastructure Report: A Focus on Nature. Retrieved from https://sustainability-coalition.org/wp-content/uploads/2023/12/Climate-Resilient-Infrastructure_A-Focus-on-Nature_Issue-2.pdf

(c) Community Engagement and Social Equity

It is imperative to prioritize community engagement and social equity in climate resilience initiatives and holistic, systemic risk management. A notable example of such collaboration is the Italy-Croatia Programme, known as ADRIJO Network. This programme connects eight Adriatic ports and cities through a digital platform, enhancing the passenger experience while promoting social, cultural, and economic development. By leveraging the cultural heritage of these ports, cities can foster mutual understanding, sustainable development, and economic competitiveness. Port spaces are reimagined as cultural and economic centres, attracting tourism, business projects, and community engagement.²⁷ The approach involves fostering partnerships with community organizations, non-governmental organizations, and other stakeholders to co-create solutions that address social vulnerabilities and promote community resilience.

(d) Innovative Technologies and Sustainable Practices

Investing in research and development is crucial for identifying and implementing cutting-edge solutions that benefit both the port and the city. For instance, Hamburg Port uses digital guidance for rail, road, and inland waterway traffic, contributing to seamless connectivity. Technology integration, including DAKOSY solutions, has transformed Hamburg into a paperless port, which is applicable to the entire traffic system of the city and port complex.²⁸

(e) Supportive and Coherent Policies at Local, State, and National Levels

In addition to the adaptation measures employed by individual ports, the role of supportive and coherent policies at the state and national levels is paramount in enhancing the overall resilience of the port ecosystem. These policies create a framework that helps align the efforts of ports, cities, and governments in effectively tackling systemic risks.



²⁷ Details available at <https://www.adrijo.eu/en/remember-project-adrijo>

²⁸ Dock the Future. (2023, November 18). Port of Hamburg as Digital Networking Pioneer. Retrieved from <https://www.docksthefuture.eu/port-of-hamburg-as-digital-networking-pioneer/>

Here are key considerations

(i) Integrated Policy Approach: Adopt an integrated policy approach at the national level to ensure that climate change adaptation and resilience strategies are mainstreamed across all sectors, including ports. This involves coordinating efforts between central government authorities responsible for ports and those overseeing climate change policies to align objectives and ensure effective implementation.

(ii) Public-Private Partnership Model Alignment: Implement mechanisms to ensure that ports operating under public-private partnership models align with national climate adaptation goals. This can be achieved by incorporating climate resilience requirements and performance indicators into the contractual agreements and regulatory frameworks that govern public-private partnerships in the port sector.

(iii) Incentives for Resilient Investments: Offer incentives and financial support mechanisms to encourage private sector investment in climate-resilient infrastructure and technologies within ports. This may include tax incentives, subsidies, grants, or preferential financing arrangements for projects demonstrating strong climate adaptation and mitigation components across the port and its systems.

(iv) Monitoring and Reporting: Establish robust monitoring and reporting mechanisms to track the implementation of climate resilience measures in ports and assess their effectiveness over time. Regular reports on climate adaptation progress can help identify gaps, evaluate the impact of policies, and inform future decision-making processes.

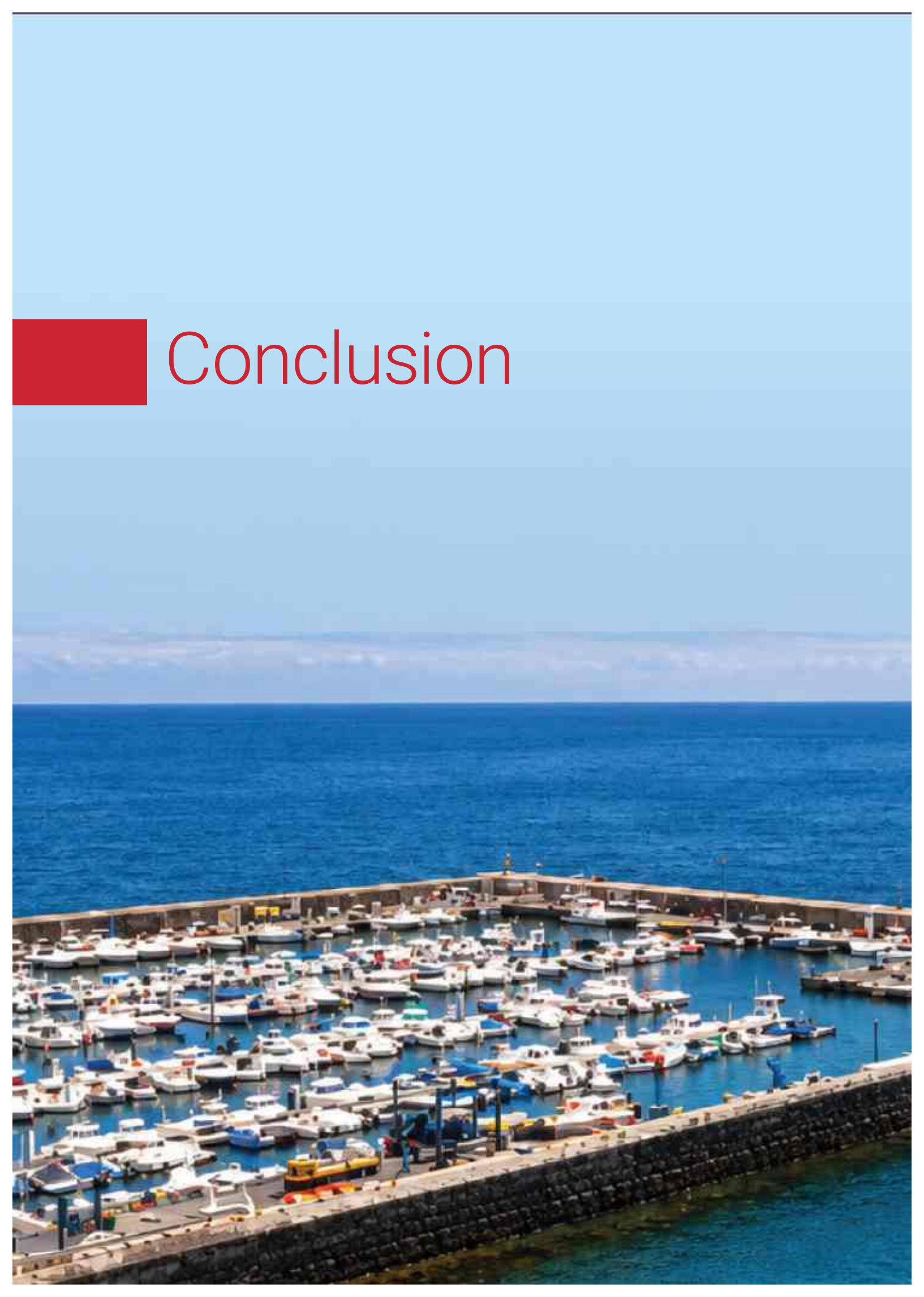
(v) Research and Knowledge Sharing: The government can create online platforms or forums where ports, academic institutions, and relevant agencies can share research findings, best practices, case studies, and innovative solutions related to climate adaptation and resilience in port operations. The public-private partnership model should include a funding allocation for collaborative research projects that address specific challenges faced by ports in adapting to climate change and developing cutting-edge solutions to enhance port resilience. The India Port Association, considered a 'think tank for the major ports with the ultimate goal of integrating the maritime sector', can facilitate and conduct research and knowledge-sharing initiatives among ports, academic institutions, and relevant agencies. Additionally, partnerships between research think tanks, port authorities, and industry stakeholders should be encouraged to conduct applied research.



(vi) International Collaboration: Similarly, stakeholders in the Indo-Pacific should prioritize a strong international collaboration to share information about climate change-related issues and adaptation and resilience strategies, particularly in the regions prone to shared climate-related challenges. Since climate change and systemic risks often transcend national boundaries, it is essential to work together. Furthermore, they can facilitate knowledge exchange programmes that allow port officials and policymakers to visit other countries and learn first-hand about successful climate adaptation strategies and technologies. Inviting international experts to share their insights and experiences with local stakeholders would also be beneficial.

To build climate-resilient ports, governments should implement strategies that promote research and knowledge sharing, enhance disaster response coordination, and foster international collaboration. This approach ensures that ports remain resilient against climate change impacts, thus safeguarding maritime trade and transportation networks. Additionally, a holistic strategy encompassing adaptive infrastructure design, contingency planning, international cooperation, climate-resilient design, ecosystem-based adaptation, stakeholder collaboration, innovative technologies, sustainable urban planning, and social integration is crucial for fortifying port resilience. By promoting and implementing supportive policies, ports can strengthen the resilience and that of the surrounding ecosystems, contributing to long-term sustainability and prosperity in the face of evolving systemic challenges.



An aerial photograph of a harbor filled with numerous white motorboats and yachts. The boats are moored in a large, rectangular stone pier. The water is a deep blue, and the sky is a clear, light blue. The pier's stone walls are visible in the foreground and along the sides of the harbor.

Conclusion

In conclusion, examining systemic risk assessment within the Visakhapatnam Port Authority and Paradip Port Authority reveals the complex dynamics and challenges inherent in managing systemic risks within seaport ecosystems. This study analyses both inter- and intra-system dynamics, highlighting achievements and identifying areas for improvement to enhance the resilience of these ports against systemic risks.

Significant progress has been made in understanding system dynamics and external influences, particularly regarding disaster risk management. There have been notable short-term achievements, such as establishing clear visions, common charters, and cohesive policies. However, existing infrastructures, which were primarily designed to withstand historic 100-year storm periods, are ill-equipped to handle emerging risks and future uncertainties. This is particularly concerning given the projected shift from a 100-year return period to a new 30-year return period, due to climate change-induced changes in extreme weather patterns. This underscores the necessity for ongoing adaptation and proactive measures to be integrated into long-term planning and decision-making processes.

Crucially, the study accentuates the urgency of mainstreaming climate change adaptation into port disaster risk reduction and systemic risk management. Even though the Sagarmala project envisages transforming existing ports into modern, world-class facilities and developing new high-capacity ports to meet evolving demands, its primary focus remains on enhancing multimodal connectivity—integrating ports with industrial clusters, hinterland regions, and evacuation networks through road, rail, inland, and coastal waterways. This integration is largely intended to position ports as engines of economic growth in coastal areas, rather than addressing long-term climate resilience.

Similarly, the Harit Sagar initiative has been introduced primarily to advance environmental sustainability at Indian ports, with a particular focus on mitigating greenhouse gas (GHG) emissions and promoting low-carbon operational practices. However, its scope remains limited in addressing the broader systemic risks posed by climate change.

Therefore, this research also advocates for incorporating the perspectives of affected communities, especially vulnerable demographics, into systemic risk management efforts to ensure the sustainability of resilience-building efforts. Understanding the characteristics of complex global systems and problems is pivotal in effective systemic risk management, which often transcends conventional approaches and demands innovative tools and practices. By acknowledging the interconnected nature of seaport ecosystems and implementing proactive measures, governments and port authorities can mitigate the broader socio-economic impacts of climate change and systemic risks. This will ensure the sustained functionality and resilience of ports and surrounding communities against evolving challenges. Furthermore, the research underscores the significance of investing in multi-hazard risk assessment, transparency/accountability mechanisms, and multi-stakeholder platforms to bolster systemic resilience in seaport ecosystems. These initiatives foster collaboration, information dissemination, and collective decision-making, thereby augmenting ports' ability to anticipate, mitigate, and respond to systemic risks effectively.

Further studies are needed to develop tools that support policymakers in understanding climate change risks, identifying region-specific adaptation needs, and determining appropriate technology requirements for integration into port adaptation plans. To support this, the study adopts a cyclic input methodology—an iterative approach well-suited to the limited data availability and complex dynamics of port systems. This methodology enhances efficiency, enables continuous learning, allows real-time adaptation, and reduces risk through early issue identification. As more data becomes available and institutional support increases, the study and its framework can continue to evolve—improving its accuracy, relevance, and effectiveness in guiding long-term systemic risk management.



National Maritime Foundation

+91 11 26156520, 26154901 ✉ maritimeindia@gmail.com
🌐 maritimeindia.org X [@nmfindia](https://twitter.com/nmfindia) LinkedIn: National Maritime Foundation



Coalition for Disaster Resilient Infrastructure

+91 11 4044 5999 ✉ info@cdri.world 🌐 www.cdri.world
✂ [@cdri_world](https://twitter.com/cdri_world) [@coalition-for-disaster-resilient-infrastructure](https://www.linkedin.com/company/coalition-for-disaster-resilient-infrastructure) [@coalitionfordri](https://www.youtube.com/channel/UC...)