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Destyanto, A.R.

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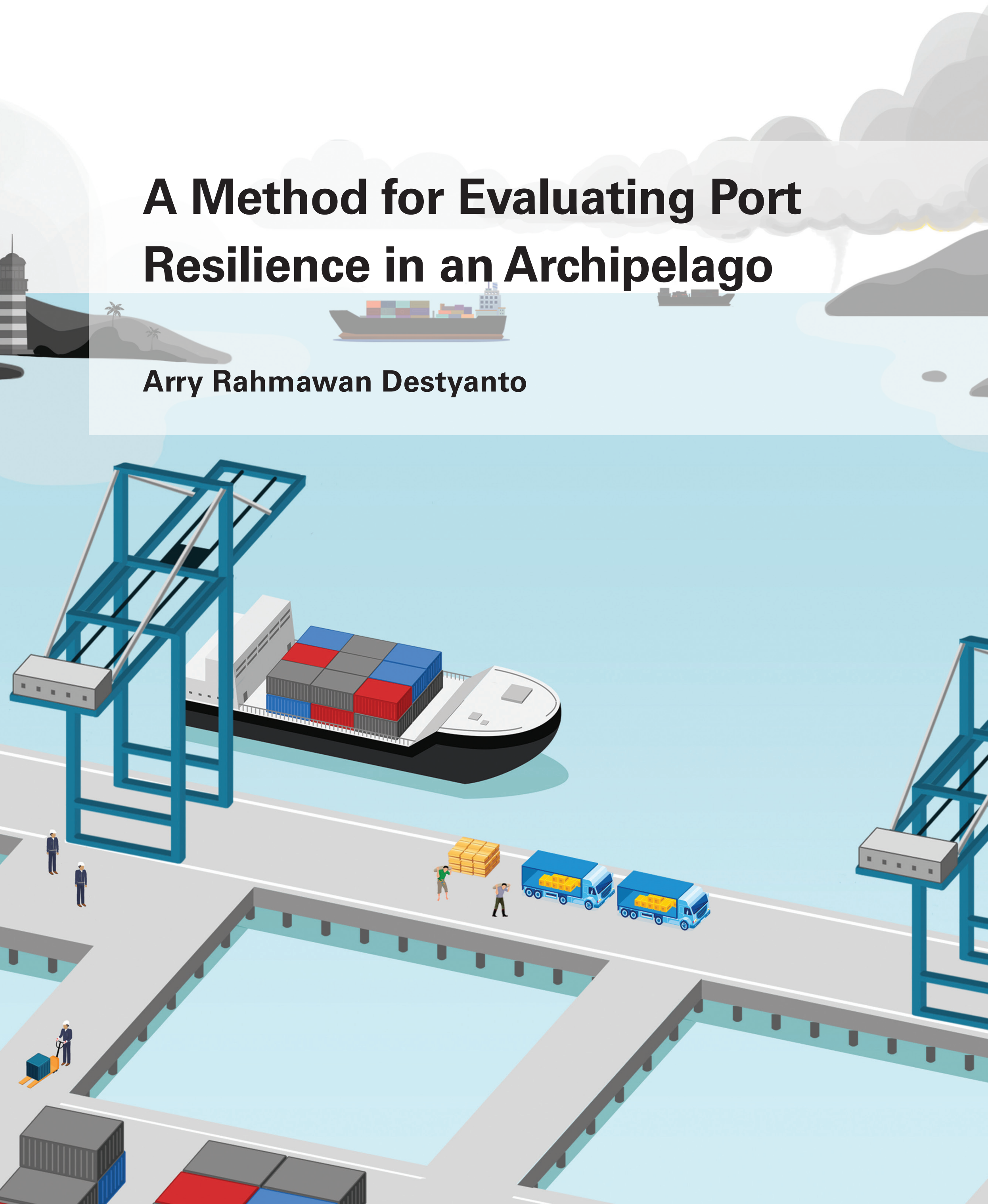

A METHOD FOR EVALUATING PORT RESILIENCE IN AN ARCHIPELAGO

Arry Rahmawan Destyanto

Delft University of Technology

A METHOD FOR EVALUATING PORT RESILIENCE IN AN ARCHIPELAGO

Dissertation

to obtain the degree of doctor
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Chair of the Board for Doctorates
to be defended publicly on
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by

Arry Rahmawan DESTYANTO
Master of Engineering
Universitas Indonesia, Indonesia
born in Tangerang, Indonesia

This dissertation has been approved by the promotors.

Composition of the doctoral committee:

Rector Magnificus,	chairperson
Prof.dr.ir. A. Verbraeck,	Delft University of Technology, promotor
Dr. Y. Huang,	Delft University of Technology, copromotor

Independent members:

Dr.ir. L.M. Hermans,	Delft University of Technology
Prof.dr.ir. L.A. Tavasszy,	Delft University of Technology
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Dr. A.O. Moeis,	Universitas Indonesia, Indonesia

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To Allah the Almighty God
my wife Melinda and my lovely children Irsyad and Khayla
without whom this dissertation would not have been completed
This dissertation is dedicated to you.

To those who are facing challenges and seeking strength.
May this dissertation offer inspiration and hope
on your journey towards resilience.

Preface

A PhD is a long, exciting, surprising, and extraordinary journey. I am very pleased to have been given the opportunity through the LPDP (Indonesia Endowment Fund for Education) scholarship program to pursue a PhD at the Faculty of Technology, Policy, and Management, TU Delft. I am grateful to have access to world-class doctoral education program, learn from renowned scientists and humble lecturers at the TRAIL research school in the Netherlands, and gain firsthand experience in becoming an independent and self-reliant researcher.

However, behind that journey, I honestly did not expect that this PhD study journey would finally end with so many unexpected challenges. For instance, the research direction suddenly changed from the initial proposal and made me lost because I was not familiar with it; I lost my father due to COVID-19 and felt guilty because I was not in Indonesia when my father passed away; I got minimal data in research; I suddenly felt alone when doing research, are some of the unexpected challenges that had made myself doubt whether this research project could be completed. At times, I even felt like giving up and quitting. But... I always remind myself that this thesis is about resilience, and there is no resilience without disruption, right? So here I would like to say that completing this study has only been possible with the help of Allah Subhanahu Wa Ta'ala, the almighty God, and the various people with whom I interacted in completing this journey.

First, I would like to express my gratitude and great thanks to my promoter and supervisor, Prof.dr.ir. Alexander Verbraeck. During my research, this is the first time I have felt guided by someone with very high academic standards who always makes me strive to give my best. I will always miss the discussion at the progress report meeting because, after the meeting, I will get a lot of feedback, insights, and fresh ideas. Apart from being a brilliant supervisor, Alexander is also a very positive person and enthusiast, and he always makes me heartened when I encounter many obstacles in this PhD journey. Not only did I learn about research materials, but I also learned many life lessons from him. I will never forget the valuable lesson that to continue to achieve the best standards in work, we do not have to sacrifice ourselves with many other roles in life as humans. From him, I learned that balancing work performance and a healthy lifestyle is the key to long-term productivity.

Secondly, I would like to thank my daily supervisor, Dr. Yilin Huang, who has always helped me advance my research progress, even when I was severely stuck. Her patience in guiding me to continue to make work plans and commitments to work on them continues to be used by me to this day, including in teaching discipline to my students. Yilin is a discipline supervisor, but she can also act as a sister and friend, and I can consult regarding matters outside of academics. I feel lucky and grateful to have a daily supervisor like Yilin. Through this page, I would also like to thank the graduation committee for being on the board of examiners and allowing me to defend my thesis.

I would also like to thank my colleagues at the Department of Industrial Engineering, Universitas Indonesia (UI), who continue to support me in completing this PhD study—special thanks to Prof. Akhmad Hidayatno, who encouraged me to move forward and leave my comfort zone. To Dr. Armand Omar Moeis and Dr. Andri Setiawan, thank you for various tips on living in the Netherlands. To Prof. Amalia Suzianti, Dr. Komarudin, Dr. Zulkarnain, Dr. rer. pol. Dr. Romadhani Ardi, and *Bu* Erlinda helped me greatly during the study extension period and encouraged me to complete this thesis. I would also like to thank A' Arif, my high school senior who helped me a lot, guided me, and ensured that I was in good condition during my stay in the Netherlands, even until I returned to Indonesia. I would also like to thank my colleagues at the Universitas Indonesia for their kindness and support.

I would also like to thank my colleagues in the Faculty of Technology, Policy, and Management at the Delft University of Technology: Bramka, Aldi, Mas Aga, Mbak Anita, Antra, Kartika & Bang Nabriz, Bahareh, Annabeth, David, Isabelle, Christopher, Anique, and Sharlene who helped me a lot to settle in, especially in the early days of being a PhD Student. Thank you for all the Go-No-Go preparation help and practical tips about surviving PhD. I would also like to thank my peer group, Mahsa, Martijn, Jordy, and Boy, who helped and encouraged me to be able to GO on the research proposal that I submitted to the committee amid the COVID-19 pandemic. Your critical feedback is the best; I am grateful to have it.

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Lastly, but most importantly. I would like to thank my lovely wife, Melinda. She is incredibly supportive and always understanding me, even at my lowest. I am sure this achievement would not have been realized without her support. Also, to my son Irsyad, from whom I learned to dare to try new things even in unfamiliar environments. Also, my little daughter Khayla was born at the same time as my birthday in 2021 in Breda; there will be no more beautiful gift on my birthday after you were born. Not to forget my beloved mother, *Bunda* Erni Yuliani, without whose prayers, guidance, and patience I could not be where I am today. For my father, *Ayah* Satto Riyanto, who passed away during the COVID-19 pandemic in 2021, I hope this thesis can also contribute a little as an addition to your good deeds. Also, I thank *Akung* Budi Cahyono and *Ati* Dian Darmawati, whose prayers never stop for us. My younger siblings, my beloved brothers and sisters, Andhita, Fauzan, Zandi, and Ita, continue to strengthen and pray for us to always be healthy and safe as a family. Thank you very much for all your support and prayers.

With the completion of this PhD, I have come to realize that I am powerless without God's help and support, which has reminded me that I have no justification for being arrogance and conceit. *La hawla wala quwwata illa billah.*

Arry Rahmawan Destyanto
Bogor, January 2025

Summary

Research Background

Ports are essential in supporting the movement of goods and people in island nations. An operationally disrupted port can disrupt the flow of goods and people, isolating communities on the island. Natural and human factors can cause this operational disruption. With the port's important role, the disruption of port operations caused by natural disasters is increasing. Global warming and climate change increase the risk of ports experiencing operational disruptions in terms of climatological risk, such as heavy rainstorms, floods, and tropical cyclones. For archipelagic countries like Indonesia, this is coupled with risks from geological hazards such as earthquakes, tsunamis, and volcanic eruptions. This increased risk means that the approach to dealing with it is no longer preventive but also responsive when a port in an archipelago is affected by a disaster. Thus, the emerging theory of *port resilience*, which can be defined as the ability to return to its original performance after being affected by disruption, is essential to be adopted so that ports in island countries have high operational resilience to support inter-island transportation of goods and people.

This research is an effort to improve the resilience of ports in archipelagic countries to natural disasters, especially large-scale archipelagic countries such as Indonesia. Indonesia is an archipelago with a high risk of natural disasters, both climate change and geological disasters. According to the United Nations (2022), one of the efforts to improve port resilience is to learn from evaluating the experience of previous incidents of port disruption. These evaluations are expected to provide lessons learned regarding success stories, lessons learned from failures, and the effectiveness of strategies used to improve port resilience.

Unfortunately, no existing structured and scientific method can objectively evaluate such incidents. Existing research in the literature on port resilience is concerned mainly with mitigation efforts and *ex-ante* analysis to estimate the level of port resilience when affected by natural disaster scenarios. The absence of a structured and scientific method to conduct *ex-post* analysis of incidents that disrupt port operations motivated and encouraged this research. The main objective of this research is to develop a scientific and structured method to help port stakeholders, especially in the archipelago, evaluate their operational resilience to natural disasters.

Research question and focus

The main research questions of this thesis are as follows:

How can port resilience to natural disasters in the archipelago be evaluated?

To achieve this, this research consolidates the definition and concept of port resilience. Once the definition and idea of port resilience are consolidated, the next step is to formulate how to operationalize the idea so that it can be used to evaluate port resilience after being affected by natural disasters in the real world. After the concept of port resilience can be operationalized, this research continues by developing a scientific and structured method for evaluating port resilience in the archipelago through four phases.

Formal guidelines used in developing evaluation methods

The next step in developing the method was to study existing approaches to developing methods for analyzing and solving problems. This research adopted the formal guidelines of McMeekin et al. (2020), who conducted a comprehensive study exploring and synthesizing the literature in creating methodological frameworks, defined as a set of practical and systematic guidelines for carrying out a particular process. Based on the synthesis of these formal guidelines, this research has four stages in developing a method for port resilience evaluation. The four stages are: (1) reviewing the literature to find the basic theoretical framework for developing the method; (2) developing the evaluation method based on the theoretical framework that has been generated; (3) testing the evaluation method against real-world case studies; and (4) reflecting on the evaluation results to determine the generalizability of the developed method.

Theoretical framework for developing the method

The first theoretical basis of this study is the literature related to the concept of resilience in port infrastructure. The results of the literature review show that there are three perspectives in viewing port resilience, namely: (1) port resilience as the ability to withstand the impact of disasters; (2) port resilience as the ability to react to disasters experienced; and (3) port resilience as the ability of how quickly the port returns to its original performance. The three perspectives above are then combined and conceptualized using a resilience curve. After that, the port resilience concept is operationalized by identifying attributes of port resilience in the literature, such as: port robustness, vulnerability, responsiveness, rapidity, and recoverability to measure port resilience based on these three perspectives.

The second theoretical basis used in developing the method in this research is the literature on the characteristics of an archipelagic country seen from the interrelationship between islands in the country. Based on the results of the literature review, it was found that islands in an archipelago should be seen as an entity that is connected to each other, also known as *island relationalities.* Using the *core-periphery* economic model*,* in an archipelago, an island will always be the main economic driver (*core*), and the surrounding islands will depend on the core island (*periphery*). Ports are the main gateways that enable the creation of these islands relationship. Based on this view, ports in island countries are seen as supporting each other, working together to meet the community's needs regarding the movement of people and goods rather than competing in business. Ports in archipelagic countries need to be seen as supporting each other, working together to meet the needs of the community for the movement of people and goods, rather than competing with each other in business. Thus, in evaluating port resilience in an archipelago, the evaluation should not only look at the internal conditions of the disrupted port but also need to be seen as an entity that is a component of a complex port network, rather than just as an independent entity.

The third theoretical basis for developing this method is the literature that shows the complexity of port operations in an archipelago by taking into account the relationship between islands. Given the relationship of the islands, the complexity of operational analysis in an archipelago consists of at least three layers of analysis. The first layer is the analysis at the port level itself, which focuses on how the social and technical components of the port interact to produce the expected port operations. Therefore, the port is seen as a complex *socio-technical* system. The second layer is an analysis of the linkages between ports and other alternative ports on the same island. This linkage is generally represented by the availability of land transportation infrastructure that connects these ports, either by road or rail. This is important given the generally cooperative nature of ports in archipelagic countries, so the level of port resilience can be influenced by the ability of alternative ports on the island to share resources or spare capacity to replace the lost capacity of the affected port. The third layer is the connectivity analysis between the affected island and other islands connected by the port. The isolation of an island can affect the resilience level of the port on the island, especially if it requires external resources from other islands to restore the port's performance.

The above three theoretical foundations are used to design a method for evaluating port resilience in archipelagic countries. The XLRM diagram was then used to structure the results of the literature review into a theoretical framework. The XLRM diagram represents exogenous uncertainties (X), policy levers (L), system relationships (R), and performance measures (M). Using XLRM, the literature review results were then framed as a whole system to be analyzed within the constraints of the four main components as a theoretical framework for developing methods to evaluate port resilience.

Development of the evaluation method based on the theoretical framework

Based on the theoretical framework, this research developed an evaluation method for port resilience in island countries into four main phases. The first phase is the analysis of port systems and island connectivity. The **first phase** operationalizes the theoretical framework of system relationships (R). The purpose of the first phase is to understand the context of the system being analyzed. The results of this analysis can be used to determine whether there is a link between port resilience and the port context. There are three types of analysis conducted in this phase, namely (1) analysis of port operations as a socio-technical system, (2) analysis of port connectivity with other alternative ports on the same island, and (3) analysis of port connectivity with ports in other islands, which is the operationalization of island shipping connectivity.

The **second phase of** the evaluation method is the port resilience curve analysis. This analysis operationalizes the performance measurement (M) theoretical framework. The metrics for measuring port performance are first determined to construct the port resilience curve. Once the metrics are specified, the port's performance is measured over time during one complete port resilience cycle. One cycle includes before, during, and after until the port performance returns to normal. After the port resilience curve is formed, the next step is to measure the resilience performance by calculating the level of *robustness, vulnerability, responsiveness, rapidity*, and *recoverability* from the curve that has been formed. This second phase is the core of the evaluation because further analysis can be done after this second phase is completed.

The **third phase of** this evaluation method is disaster impact analysis. The disaster impact analysis is an operationalization of the theoretical framework of how exogenous uncertainty (X) represented by natural disasters affects the condition of the system relationship (R). The analysis in this phase focuses on investigating the extent to which natural disasters impact port resilience and island relationalities. In this phase, the three types of analysis are again conducted, as in the first phase, but the study is conducted after the disaster affects the port. This third phase aims to determine how far a disaster has impacted the port infrastructure and island connectivity affected by the disaster.

The **fourth phase of** this evaluation method is the analysis of interventions or strategies taken to improve port resilience to natural disasters. This analysis consists of four timeframes based on the time division on the port resilience curve. The results of this fourth phase are expected to provide lessons regarding what interventions are effective or not in increasing port resilience to natural disasters. The analysis results of these four phases are then synthesized to draw lessons that hopefully can enhance the resilience of the port concerned in the future or the resilience of other ports with a similar context.

Application of the evaluation method to real-world case studies

This study tested the method on three real-world case studies. The three case studies are selected from Indonesia, an archipelago with many islands, ports, and natural disaster risks that can affect port operations. The case studies used in this study are as follows:

Case Study 1: *Pantoloan Port after Central Sulawesi Earthquake and Tsunami in 2018*

The first application of this method is to evaluate the resilience of Pantoloan Port when port operations were disrupted in the 2018 Earthquake and Tsunami disaster. In this case study, Pantoloan Port represents implementing the method at a large port in Indonesia, serving container loading and unloading, which is commercial and a major port in the hierarchy of seaports in Indonesia. In addition, the September 28, 2018 incident represents the implementation process in the context of a geological disaster, specifically a 7.5 Mw earthquake and tsunami.

The four phases of the port resilience evaluation method were successfully applied to the context of the Pantoloan Port case study. The results of the port resilience evaluation using the port resilience curve show that it takes 296 days for Pantoloan Port to restore the performance from the disaster to the normal port performance before the disaster. The various data and the implementation process of each of the four phases of this method are explained more fully and in detail in Chapter 4. The chapter also describes various lessons learned that can be taken to improve the resilience of Pantoloan Port, particularly in the future or other ports in general that have characteristics similar to Pantoloan Port derived from implementing the four-phase evaluation method.

Case Study 2: *Seba Port after Tropical Cyclone Seroja in 2021*

The second application of this method is to evaluate the resilience of Seba Port, located on Sabu Island, a small island in East Nusa Tenggara Province, when the port operations were disrupted by the incident of Tropical Cyclone Seroja in 2021. This case study provides a sample expected to be representative of a small port, located far from the main island, that is a non-commercial public port and serves the transportation of non-containerized goods on Sabu Island. The incident, which occurred on April 6, 2021, also represents the implementation process of the method on a meteorological disaster, specifically the 102 km/h tropical cyclone winds that hit the port.

This case study result shows that implementing all four phases of the port resilience evaluation method at Seba Port can be applied well despite the limited availability of public data. The results of the resilience evaluation using the port resilience curve showed that it took 261 days for Seba Port to return to normal port performance since the impact of Cyclone Seroja. The data used and the process of implementing the four phases of the evaluation method is described more fully in Chapter 5. The analysis results of the four phases are then used to draw valuable lessons that can be used to improve the resilience of Seba Port in the future or other ports with a similar context to Seba Port.

Case Study 3: *Mamuju Simboro Port after Majene Earthquake in 2021*

The third application of this method is to evaluate the resilience of Mamuju Simboro Port in West Sulawesi, whose operations were affected by the 6.2 Mw West Sulawesi Earthquake on January 15, 2021. This case study provides a sample for implementing the method in a medium-sized port serving passenger vessel shipping traffic and a commercial port, which has different characteristics from the previous two ports. This case study also represents the implementation process in the context of a geological disaster, specifically a 6.2 Mw earthquake.

This case study shows that implementing all four phases of the port resilience evaluation method at Mamuju Port is feasible despite the limited availability of public data and difficult access to primary data. The resilience evaluation results using the port resilience curve show that it takes 427 days for the port to restore its performance to normal after the disaster. The analysis results of the four phases are then used to draw lessons and insights that can be the basis for strengthening the resilience of Mamuju Simboro Port in the future or other ports similar to Mamuju Simboro Port.

Reflection on the results and generalization of the method

Based on the process and results of the method implementation in the three case studies, it can be concluded that the method was successfully applied and provided the expected analysis output. What are the implications of successfully using the method for the three case studies? As an archipelago, Indonesia has approximately 3,224 ports that support island connectivity and interconnectedness. Of the total number of ports, 81% are ports whose characteristics are similar or represented in the three case studies. Thus, based on the results obtained in this study, this method is quite flexible and can be used on 81% of ports in Indonesia that have similar contexts or characteristics to the three case studies, provided that the data needed to conduct the analysis is available, complete, and accessible. The implementation process results show that the need for more data or difficulty accessing the required data will make this method complex, complicated, and time-consuming. Further research can be done to test the effectiveness of this method on port operations that fall into the 81% characteristic category but have a very extreme port size, be it too large or a tiny port.

For generalization and utilization of this method to ports in archipelagic countries other than Indonesia, it can first be matched whether the port size, disaster, and island to be evaluated have similar characteristics to the case study exemplified in this study. Suppose there are many similar characteristics between the three aspects. In that case, the application of the method can be directly followed by what has been described in this study through Chapters 4 to 6. This method is very flexible and can be used in the context of most ports in a large-scale archipelago. However, the quality and availability of the data required for the analysis are also crucial for successfully using this method. This will raise awareness for port stakeholders in the archipelago so they can start preparing the data needed for port resilience to be appropriately evaluated. Examples of the required data as described in this study can be an opening road regarding what types of data need to be prioritized to be collected from now on so that the port resilience evaluation process can be carried out more easily and quickly.

As for using this method in ports with operational characteristics outside the case study, further research is needed depending on the context of the port being evaluated. For example, another 19% of ports in Indonesia are specialized ports with highly specialized port functions. Examples are ports or terminals specialized for loading and unloading raw materials or finished goods in the plantation, livestock, fishery, mining, agriculture, or forestry industries. Each port has distinctive operational characteristics, so applying this method will likely require adjustments. Thus, the phases prepared and the analytical tools in this method need to be reviewed to determine whether they are appropriate and suitable for the type of port under study and whether the required data are available in terms of quality and quantity.

Conclusion

This dissertation and research were created to develop a scientific and structured method to help port stakeholders in island nations evaluate the resilience of their ports to natural disasters that have already occurred (*ex-post analysis*). The main challenges in creating a comprehensive yet practically applicable method are the complexity of archipelagic countries consisting of interconnected islands (*island relationalities*), the complexity of ports as *socio-technical* systems, and inconsistent definitions and concepts of port resilience to natural disasters. This study focuses on developing a method with these three considerations in mind, where other influencing factors are beyond the scope of this study.

The general conclusion is that this study's four-phase port resilience evaluation method conforms to scientific principles and can be applied in different port contexts. This evaluation method consists of four phases: (1) port system and island connectivity analysis, (2) port resilience curve analysis, (3) disaster impact analysis, and (4) port resilience intervention analysis. The three case studies, Pantoloan Port, Seba Port, and Mamuju Port, show that the four phases can be applied well in the three ports. The analysis results of each phase were then synthesized to provide various lessons for future port resilience strengthening.

A critical lesson from the development and implementation process of this port resilience evaluation method is that it is a data-dependent method. In other words, studying objects without complete and accurate data to analyze the four phases will cause obstacles in using this method. Applying this method to a port case study that does not have complete data shows how challenging and time-consuming the implementation process can be. This implies that evaluating port resilience requires not only a structured and scientific method but also the existence of data to analyze. For a pragmatic evaluation of public ports, this study recommends that ports worldwide start collecting data that facilitates analysis in Phase 2 and Phase 4, as these are the core phases of port resilience evaluation.

Meanwhile, ports in island countries, in addition to phases 2 and 4, need to prepare infrastructure or procedures for how to have complete and accurate data to facilitate analysis in phases 1 and 3, which also consider the spatial aspects of the archipelago in conducting port resilience evaluations. Through the scientific and structured port resilience evaluation produced in this study, port stakeholders in the island and non-island countries can independently evaluate their port resilience. The evaluation results can be collected and become collective knowledge to improve port resilience in island nations worldwide. This method and its derivatives can also fill the missing pieces in practical United Nations guidance (UNCTAD, 2022) on enhancing port resilience capacity.

Ringkasan

Latar Belakang Penelitian

Pelabuhan memiliki peranan penting dalam menunjang perpindahan barang dan orang di negara kepulauan. Pelabuhan yang secara operasional terdisrupsi dapat menyebabkan terganggunya arus barang dan orang, menyebabkan masyarakat di pulau tersebut terisolir. Disrupsi operasional ini dapat disebabkan karena faktor alam dan juga faktor dari manusia. Dengan peran pelabuhan yang penting tersebut, tren terganggunya operasional pelabuhan yang disebabkan bencana alam justru semakin meningkat. Adanya pemanasan global dan climate change memperbesar risiko pelabuhan – pelabuhan di dunia mengalami disrupsi operasional dari sisi climatological risk, seperti hujan badai yang sangat deras, banjir, dan tropical cyclone. Untuk negara kepulauan, seperti Indonesia, hal ini ditambah dengan risiko dari geological risk seperti gempa bumi, tsunami, dan letusan gunung berapi. Meningkatnya risiko ini membuat pendekatan menanganinya tidak lagi dengan upaya preventif, namun juga upaya responsif apabila pelabuhan di kepulauan terdampak bencana. Sehingga, teori yang sedang berkembang saat ini yaitu ketahanan pelabuhan (bahasa Inggris: *port resilience*), yang secara sederhana dapat diartikan sebagai kemampuan untuk kembali ke performa semula setelah terdampak disrupsi, menjadi penting untuk dapat diadopsi agar pelabuhan di negara – negara kepualauan memiliki ketahanan operasional yang tinggi untuk mendukung transportasi barang dan orang antar pulau.

Penelitian ini merupakan salah satu upaya untuk meningkatkan ketahanan pelabuhan di negara – negara kepulauan terhadap bencana alam, terutama negara - negara kepulauan skala besar seperti Indonesia. Indonesia merupakan negara kepulauan yang memiliki risiko tinggi terhadap bencana alam, baik bencana karena perubahan iklim maupun bencana geologis. Menurut United Nations (2022), salah satu upaya meningkatkan resiliensi pelabuhan adalah dengan belajar dari evaluasi terhadap pengalaman insiden – insiden terdisrupsinya pelabuhan yang sebelumnya. Evaluasi tersebut diharapkan dapat memberikan pembelajaran terkait cerita sukses, pelajaran dari kegagalan, dan tingkat efektivitas dari strategi – strategi yang digunakan untuk meningkatkan ketahanan pelabuhan.

Sayangnya, belum ada metode terstruktur dan ilmiah yang dapat digunakan untuk melakukan evaluasi insiden tersebut secara objektif. Penelitian yang ada di literatur saat terkait port resilience kebanyakan berkutat pada upaya mitigasi dan analisis yang bersifat *ex-ante* untuk mengestimasi tingkat resiliensi pelabuhan apabila terdampak skenario – skenario bencana alam. Tidak adanya metode terstruktur dan ilmiah untuk melakukan *ex-post* analisis dari insiden – insiden yang membuat operasional pelabuhan terganggu memotivasi dan mendorong diadakannya penelitian ini. Tujuan utama dari penelitian ini adalah mengembangkan sebuah metode yang ilmiah dan terstruktur untuk membantu pelabuhan – pelabuhan di negara kepulauan dalam melakukan evaluasi ketahanan operasional terhadap bencana alam.

Pertanyaan dan fokus penelitian

Pertanyaan penelitian utama dari thesis ini adalah sebagai berikut:

Bagaimana ketahanan pelabuhan terhadap bencana alam di negara kepulauan dapat dievaluasi?

Untuk mencapai hal tersebut, penelitian ini berfokus untuk mengkonsolidasi definisi dan konsep dari apa itu ketahanan pelabuhan. Setelah definisi dan konsep ketahanan pelabuhan dikonsolidasi, maka selanjutnya adalah merumuskan bagaimana cara mengoperasionalisasikan konsep tersebut agar dapat digunakan untuk mengevaluasi ketahanan pelabuhan setelah terdampak bencana alam di dunia nyata. Setelah konsep ketahanan pelabuhan dapat dioperasionalisasikan, maka penelitian ini dilanjutkan dengan mengembangkan metode ilmiah dan terstruktur untuk mengevaluasi ketahanan pelabuhan yang terdiri atas empat fase utama.

Panduan formal yang digunakan dalam mengembangkan metode evaluasi

Untuk mengembangkan metode, langkah berikutnya yang dilakukan adalah mempelajari berbagai pendekatan - pendekatan eksisting dalam pengembangan metode untuk melakukan analisis dan memecahkan masalah. Penelitian ini mengadopsi panduan formal dari McMeekin et al. (2020) yang telah melakukan studi komprehensif dalam mengeksplorasi dan melakukan sintesis dari literatur - literatur dalam menciptakan metode, yang diartikan sebagai sebuah set dari panduan praktis dan sistematis untuk melaksanakan suatu proses tertentu. Berdasarkan dari hasil sintesis panduan formal tersebut, penelitian ini memiliki empat tahapan dalam mengembangkan metode untuk evaluasi ketahanan pelabuhan. Keempat tahapan tersebut adalah: (1) meninjau literatur untuk menemukan kerangka dasar teori dalam mengembangkan metode; (2) mengembangkan metode evaluasi berdasarkan kerangka teoretik yang telah dihasilkan; (3) menguji metode evaluasi tersebut terhadap studi kasus yang ada di dunia nyata; dan (4) melakukan refleksi dari hasil evaluasi untuk mengetahui kemampuan generalisasi metode yang dikembangkan.

Kerangka dasar teoretik untuk mengembangkan metode

Titik berangkat utama dari studi ini adalah literatur – literatur terkait dengan konsep ketahanan pada infrastruktur pelabuhan. Hasil tinjauan literatur menunjukkan ada tiga perspektif dalam memandang ketahanan pelabuhan, yaitu: (1) ketahanan pelabuhan sebagai kemampuan untuk menahan dampak bencana; (2) ketahanan pelabuhan sebagai kemampuan memberikan reaksi atas bencana yang dialami; dan (3) ketahanan pelabuhan sebagai kemampuan seberapa cepat pelabuhan kembali ke performa semula. Ketiga perspektif diatas kemudian digabungkan lalu dikonseptualisasikan menggunakan kurva ketahanan pelabuhan (*port resilience curve*). Setelah itu, konsep ketahanan pelabuhan tersebut dioperasionalisasikan dengan mengidentifikasi atribut

– atribut operasionalisasi ketahanan pelabuhan yang ada di dalam literatur, seperti: *port robustness, vulnerability, responsiveness, rapidity,* dan *recoverability* untuk mengukur ketahanan pelabuhan berdasarkan tiga perspektif tersebut.

Dasar teori kedua yang digunakan dalam mengembangkan metode pada penelitian ini adalah literatur mengenai karakteristik dari sebuah negara kepulauan dilihat dari keterkaitan hubungan antar pulau di negara tersebut. Berdasarkan dari hasil kajian literatur ditemukan bahwa pulau – pulau di sebuah negara kepulauan harus dilihat sebagai sebuah entitas yang terhubung satu sama lain, dikenal juga sebagai *island relationalities.* Menggunakan model ekonomi *core-periphery,* sebuah negara kepulauan selalu memiliki pulau sebagai penggerak ekonomi utama (*core*) dan juga pulau – pulau sekitarnya yang bergantung kepada pulau inti tersebut (*periphery*). Pelabuhan merupakan gerbang utama yang menjadi *enabler* terciptanya hubungan antar pulau ini.

Berdasarkan cara pandang ini, pelabuhan di negara – negara kepulauan dipandang sebagai pelabuhan yang saling mendukung satu sama lain, bekerjasama untuk memenuhi kebutuhan masyarakat baik melakukan perpindahan orang maupun barang, ketimbang saling berkompetisi secara bisnis. Sehingga, dalam melakukan evaluasi ketahanan pelabuhan di negara kepulauan, evaluasi tidak hanya dilihat dari kondisi internal pelabuhan yang terdisrupsi saja namun juga perlu dilihat sebagai sebuah entitas yang merupakan komponen dari jaringan pelabuhan yang kompleks, alih – alih hanya sebagai sebuah entitas yang independen.

Dasar teori ketiga yang menjadi landasan untuk mengembangkan metode ini adalah literatur yang menunjukkan kompleksitas operasional di negara kepulauan dengan memperhatikan adanya keterkaitan antara satu pulau dengan pulau lainnya. Dengan adanya keterkaitan antar pulau ini, maka kompleksitas analisis operasional di negara kepulauan sekurang – kurangnya terdiri dari tiga lapisan analisis. Lapisan pertama adalah analisis pada tingkat pelabuhan itu sendiri, yang berfokus untuk mengetahui bagaimana interaksi komponen sosial dan teknis pelabuhan dalam menghasilkan operasional pelabuhan sesuai dengan yang diharapkan. Untuk itu, pelabuhan dilihat sebagai sebuah sistem *socio-technical* yang kompleks. Lapisan kedua adalah lapisan analisis keterkaitan antara pelabuhan di sebuah pulau dengan pelabuhan alternatif lainnya di pulau yang sama. Keterkaitan ini umumnya diwakili dengan ketersediaan infrastruktur transportasi darat yang menghubungkan pelabuhan – pelabuhan tersebut, baik melalui jalan raya atau rel kereta api. Hal ini penting mengingat secara umum sifat pelabuhan di negara kepulauan adalah kooperatif, sehingga tingkat ketahanan pelabuhan dapat dipengaruhi dari kemampuan pelabuhan alternatif di pulau tersebut untuk berbagi sumber daya atau kapasitas cadangan untuk menggantikan kapasitas pelabuhan terdampak yang hilang. Lapisan ketiga adalah lapisan analisis konektivitas antara pulau yang terdampak dengan pulau lainnya yang dihubungkan dengan pelabuhan. Analisis konektivitas ini penting untuk memastikan sumber daya yang dibutuhkan oleh pulau dan pelabuhan terdampak masih dapat masuk atau keluar dari pulau lain. Terisolirnya suatu pulau dapat mempengaruhi tingkat ketahanan pelabuhan di pulau tersebut, khususnya apabila membutuhkan sumber daya dari luar untuk mengembalikan performa pelabuhan seperti semula.

Tiga landasan teori di atas, yaitu teori ketahanan pada infrastruktur pelabuhan, karakteristik spasial di negara kepulauan, serta kompleksitas operasional pelabuhan di negara kepulauan, digunakan untuk merancang metode evaluasi ketahanan pelabuhan di negara kepulauan. XLRM diagram kemudian digunakan untuk menstrukturkan hasil tinjauan literatur ke dalam bentuk kerangka teoretik. XLRM diagram merepresentasikan ketidakpastian eksogen (X), pengungkit kebijakan (L), hubungan sistem (R), dan pengukuran performa (M). Dengan menggunakan XLRM, hasil tinjauan literatur kemudian dibingkai sebagai sebuah sistem utuh untuk dianalisis dengan batasan empat komponen utama tadi sebagai kerangka teoretik dalam pengembangan metode untuk mengevaluasi ketahanan pelabuhan.

Pengembangan metode evaluasi berdasarkan kerangka teoretik

Berdasarkan kerangka teoretik yang telah disusun, penelitian ini mengembangkan metode evaluasi ketahanan pelabuhan di negara kepulauan ke dalam empat fase utama. Fase pertama adalah analisa sistem pelabuhan dan konektivitas pulau. **Fase pertama** ini merupakan operasionalisasi dari kerangka teoretik hubungan sistem (R). Tujuan dari dilakukannya fase pertama adalah untuk memahami konteks dari sistem yang dianalisis. Hasil dari analisis ini dapat digunakan untuk menghubungkan apakah ada keterkaitan antara ketahanan pelabuhan dengan konteks pelabuhannya. Terdapat tiga jenis analisis yang dilakukan pada fase ini, yaitu (1) analisis operasional pelabuhan sebagai sistem sosio-teknikal; (2) analisis konektivitas pelabuhan dengan pelabuhan alternatif lain di pulau yang sama melalui infrastruktur darat (*hinterland*); dan (3) analisis konektivitas pulau dengan pulau lainnya (*shipping connectivity*).

Fase kedua dari metode evaluasi ini adalah analisis kurva ketahanan pelabuhan. Analisis ini merupakan operasionalisasi dari kerangka teoretikal pengukuran performa (M). Untuk menyusun kurva ketahanan pelabuhan, metrik untuk mengukur performa pelabuhan ditentukan terlebih dulu. Setelah metrik ditentukan, maka performa dari pelabuhan tersebut diukur seiring berjalannya waktu selama satu siklus ketahanan pelabuhan. Satu siklus ketahanan ini meliputi sebelum, saat, setelah, hingga performa pelabuhan kembali normal atau lebih baik dari sebelumnya. Setelah kurva ketahanan pelabuhan terbentuk, berikutnya adalah mengukur performa ketahanan dengan menghitung tingkat dari *robustness, vulnerability, responsiveness, rapidity,* dan *recoverability* dari kurva yang telah terbentuk. Fase kedua ini merupakan inti evaluasi karena nantinya analisis lebih lanjut dapat dilakukan setelah fase kedua ini selesai.

Fase ketiga dari metode evaluasi ini adalah analisis dampak bencana. Analisis dampak bencana ini merupakan operasionalisasi dari kerangka teoretik bagaimana ketidakpastian eksogen (X) yang direpresentasikan dengan bencana alam mempengaruhi kondisi dari hubungan sistem (R). Analisis pada fase ini berfokus untuk menyelidiki seberapa jauh bencana alam memberikan dampak pada ketahanan pelabuhan dan juga hubungan antar pulau. Pada fase ini, tiga jenis analisis seperti di fase pertama kembali dilakukan, namun analisis tersebut dilakukan pasca pelabuhan terdampak bencana. Fase ketiga ini bertujuan untuk mengetahui seberapa jauh suatu bencana memberikan dampak terhadap infrastruktur pelabuhan dan konektivitas pulau yang terdampak bencana tersebut.

Fase keempat dari metode evaluasi ini adalah analisis intervensi atau strategi yang diambil untuk meningkatkan ketahanan pelabuhan terhadap bencana alam. Analisis ini dilakukan berdasarkan pembagian fase siklus ketahanan pelabuhan yang terdiri dari empat kerangka waktu berdasarkan kurva ketahanan pelabuhan. Hasil dari fase keempat ini diharapkan dapat memberikan pelajaran terkait apa saja intervensi yang efektif atau tidak dalam meningkatkan ketahanan pelabuhan terhadap bencana alam. Hasil analisis dari empat fase ini kemudian disintesis untuk diambil pelajaran yang harapannya dapat menguatkan ketahanan pelabuhan yang bersangkutan di masa yang akan datang atau ketahanan pelabuhan lainnya yang memiliki konteks yang mirip.

Aplikasi metode evaluasi pada studi kasus di dunia nyata

Studi ini melakukan ujicoba metode yang telah disusun pada tiga studi kasus di dunia nyata. Tiga studi kasus tersebut berasal dari Indonesia, sebuah negara kepulauan yang terdiri dari banyak pulau, pelabuhan, dan risiko bencana alam yang dapat mempengaruhi operasional pelabuhan. Adapun studi kasus yang digunakan dalam studi ini antara lain adalah sebagai berikut:

Studi Kasus 1: *Pelabuhan Pantoloan pasca Gempa Bumi dan Tsunami Sulawesi Tengah pada Tahun 2018*

Aplikasi pertama dari metode ini adalah untuk mengevaluasi ketahanan Pelabuhan Pantoloan saat operasional pelabuhan terdisrupsi pada insiden Gempa Bumi dan Tsunami 2018. Pada studi kasus ini, Pelabuhan Pantoloan mewakili implementasi metode pada pelabuhan berukuran besar di Indonesia, melayani bongkar muat peti kemas, bersifat komersial, dan merupakan pelabuhan utama dalam hirarki pelabuhan laut di Indonesia. Selain itu, insiden yang terjadi pada 28 September 2018 ini mewakili proses implementasi pada konteks bencana geologis, khususnya bencana gempa bumi sebesar 7.5 Mw dan tsunami.

Keempat fase pada metode evaluasi ketahanan pelabuhan berhasil diterapkan untuk konteks studi kasus Pelabuhan Pantoloan. Hasil evaluasi ketahanan pelabuhan menggunakan kurva ketahanan pelabuhan menunjukkan bahwa dibutuhkan waktu selama 296 hari bagi Pelabuhan Pantoloan untuk mengembalikan performa sejak terdampak bencana menuju kepada performa pelabuhan seperti normal saat sebelum terjadinya bencana. Adapun berbagai data dan proses implementasi dari masing – masing empat fase metode ini dijelaskan dengan lebih lengkap dan detil pada Bab 4. Pada Bab tersebut juga dijelaskan berbagai pembelajaran yang bisa diambil untuk meningkatkan ketahanan Pelabuhan Pantoloan pada khususnya di masa yang akan datang, atau Pelabuhan lain pada umumnya yang memiliki karakteristik yang mirip dengan Pelabuhan Pantoloan yang diturunkan dari implementasi metode empat fase evaluasi.

Studi Kasus 2: *Pelabuhan Seba pasca Angin Siklon Seroja pada Tahun 2021*

Aplikasi kedua dari metode ini adalah untuk mengevaluasi ketahanan Pelabuhan Seba yang terletak di Pulau Sabu, sebuah pulau kecil di Provinsi Nusa Tenggara Timur, saat operasional pelabuhan terdisrupsi oleh insiden Angin Siklon Tropis Seroja pada 2021. Studi kasus ini menjadi sampel yang diharapkan dapat mewakili pelabuhan dengan ukuran kecil, terletak jauh dari pulau utama, merupakan pelabuhan umum non-komersial, dan melayani pengangkutan barang non-peti kemas di Pulau Sabu. Insiden yang terjadi pada tanggal 6 April 2021 ini juga mewakili proses implementasi pada konteks bencana meteorologis, khususnya angin siklon tropis berkecepatan 102 km/jam yang menghantam pelabuhan.

Studi kasus ini menunjukkan bahwa implementasi keempat fase metode evaluasi ketahanan pelabuhan di Pelabuhan Seba dapat diterapkan dengan baik, di tengah ketersediaan data publik yang terbatas. Hasil evaluasi ketahanan menggunakan kurva ketahanan pelabuhan menunjukkan bahwa diperlukan waktu 261 hari bagi Pelabuhan Seba untuk mengembalikan performa pelabuhan ke dalam kondisi normal sejak terdampaknya Angin Siklon Seroja. Data yang digunakan serta proses implementasi empat fase pada metode evaluasi dijelaskan dengan lebih lengkap pada Bab 5. Hasil analisis dari empat fase tersebut kemudian digunakan untuk menarik pelajaran berharga yang dapat digunakan untuk meningkatkan ketahanan Pelabuhan Seba di masa yang akan datang, atau Pelabuhan lainnya yang memiliki konteks yang mirip dengan Pelabuhan Seba.

Studi Kasus 3: *Pelabuhan Mamuju Simboro pasca Gempa Bumi Sulawesi Barat pada tahun 2021*

Aplikasi ketiga dari metode ini adalah untuk mengevaluasi ketahanan Pelabuhan Mamuju Simboro yang di Sulawesi Barat yang operasionalnya terdampak insiden Gempa Bumi di Sulawesi Barat sebesar 6.2 Mw pada 15 Januari 2021. Studi kasus ini menjadi sampel dalam mengimplementasikan metode di pelabuhan dengan ukuran sedang, melayani lalu lintas pelayaran kapal penumpang, dan merupakan pelabuhan bersifat komersial, di mana pelabuhan ini berbeda karakteristik dengan dua pelabuhan sebelumnya. Studi kasus ini juga mewakili bagaimana proses implementasi pada konteks bencana geologis, khususnya gempa bumi sebesar 6.2 Mw.

Studi kasus ini menunjukkan bahwa implementasi keempat fase metode evaluasi ketahanan pelabuhan di Pelabuhan Mamuju dapat diterapkan dengan baik, di tengah ketersediaan data publik yang terbatas, serta akses ke data primer yang sulit. Hasil evaluasi ketahanan menggunakan kurva ketahanan pelabuhan menunjukkan bahwa diperlukan waktu 427 hari bagi pelabuhan untuk dapat mengembalikan performanya kembali seperti normal pasca terdampak bencana. Proses implementasi metode dengan lebih detil serta berbagai macam data yang digunakan dijelaskan lebih lengkap pada bab 6. Hasil analisis pada keempat fase tersebut kemudian digunakan untuk menarik pelajaran dan wawasan yang dapat menjadi dasar penguatan ketahanan pelabuhan Mamuju Simboro di masa yang akan datang atau juga pelabuhan lainnya yang sejenis atau mirip dengan Pelabuhan Mamuju Simboro.

Refleksi hasil dan generalisasi metode

Berdasarkan pada proses dan hasil implementasi metode pada ketiga studi kasus, dapat diketahui bahwa metode ini berhasil diterapkan dan mampu memberikan keluaran hasil analisis seperti yang diharapkan. Apa implikasi dari keberhasilan penggunaan metode ini terhadap tiga studi kasus insiden yang berbeda tersebut? Pada konteks Indonesia sebagai negara kepulauan, terdapat kurang lebih 3,224 pelabuhan di satu negara yang menunjang konektivitas serta keterhubungan pulau. Dari total jumlah pelabuhan tersebut, 81% di antaranya merupakan pelabuhan yang karakteristiknya mirip atau terwakili di tiga studi kasus tersebut. Sehingga, berdasarkan hasil yang didapatkan pada studi ini, metode ini cukup fleksibel dan dapat digunakan pada 81% pelabuhan di Indonesia yang memiliki konteks atau karakteristik yang mirip dengan ketiga studi kasus tersebut dengan catatan bahwa data yang dibutuhkan untuk melakukan analisis tersedia, lengkap, dan dapat diakses. Hasil dari proses implementasi menunjukkan bahwa semakin sedikitnya data atau sulitnya mengakses data yang dibutuhkan maka akan membuat implementasi metode ini menjadi sangat kompleks, rumit, dan memakan waktu yang sangat lama. Penelitian lebih jauh dapat dilakukan untuk menguji efektivitas metode ini pada operasional pelabuhan yang termasuk pada kategori karakteristik 81% tersebut, namun memiliki ukuran pelabuhan yang sangat ekstrim, baik itu terlalu besar atau pelabuhan yang sangat kecil.

Untuk generalisasi dan pemanfaatan metode ini pada pelabuhan di negara kepulauan selain Indonesia, dapat dicocokkan terlebih dulu apakah ukuran pelabuhan, bencana dan pulau yang akan dievaluasi memiliki karakteristik yang mirip dengan studi kasus yang dicontohkan pada studi ini. Apabila terdapat banyak kesamaan karakteristik antara ketiga aspek tersebut, maka penerapan metode dapat langsung mencontoh dengan apa yang sudah dijelaskan pada studi ini melalui Bab 4 hingga 6. Metode ini sangat fleksibel untuk digunakan dalam konteks mayoritas pelabuhan di negara kepulauan. Namun, kualitas dan ketersediaan data yang dibutuhkan untuk analisis juga penting untuk menunjang keberhasilan penggunaan metode ini. Hal ini diharapkan dapat meningkatkan kesadaran bagi pemangku kepentingan pelabuhan di negara kepulauan untuk mulai mempersiapkan data – data yang dibutuhkan agar ketahanan pelabuhan dapat dievaluasi dengan baik. Contoh – contoh data yang dibutuhkan seperti yang telah dijelaskan pada studi ini semoga dapat menjadi jalan pembuka terkait jenis data apa yang perlu diprioritaskan untuk dikumpulkan mulai saat ini agar proses evaluasi ketahanan pelabuhan dapat dilakukan dengan lebih mudah dan cepat.

Sementara untuk penggunaan metode ini pada pelabuhan dengan karakteristik operasional di luar studi kasus, perlu dibuat penelitian lebih lanjut tergantung dari konteks pelabuhan yang dievaluasi. Sebagai contoh, 19% pelabuhan lainnya di Indonesia merupakan pelabuhan – pelabuhan khusus dengan fungsi pelabuhan yang sangat terspesialisasi. Sebagai contoh adalah pelabuhan atau terminal – terminal yang dikhususkan untuk melakukan bongkar muat dari bahan baku atau barang jadi di industri perkebunan, peternakan, perikanan, pertambangan, pertanian, attau perhutanan. Masing – masing dari pelabuhan ini memiliki ciri operasional yang sangat khas sehingga aplikasi dari metode ini sangat mungkin memerlukan penyesuaian dalam prosesnya. Sehingga, fase yang disusun serta alat bantu analisis pada metode ini perlu ditinjau kembali apakah sudah sesuai dan cocok dengan jenis pelabuhan yang diteliti, serta apakah data – data yang dibutuhkan tersedia baik secara kualitas dan kuantitasnya.

Kesimpulan

Disertasi dan penelitian ini dibuat untuk menyusun sebuah metode yang ilmiah dan terstruktur untuk membantu pemangku kepentingan pelabuhan di negara kepulauan untuk dapat mengevaluasi ketahanan pelabuhan mereka terhadap bencana alam yang sudah terjadi (*ex-post analysis*). Kompleksitas negara kepulauan yang terdiri dari pulau – pulau yang saling terhubung (*island relationalities*), kompleksitas pelabuhan sebagai sebuah sistem *socio-technical,* serta definisi dan konsep ketahanan pelabuhan terhadap bencana alam yang inkonsisten menjadi tantangan utama dalam menciptakan metode yang komprehensif namun juga dapat diaplikasikan secara praktis. Studi ini fokus dalam mengembangkan metode dengan cakupan pertimbangan tiga hal di atas, di mana faktor lain yang mempengaruhi berada di luar cakupan studi ini.

Kesimpulan umum yang dapat diambil adalah bahwa metode evaluasi ketahanan pelabuhan di daerah kepulauan yang terdiri dari empat fase implementasi pada penelitian ini sudah sesuai dengan kaidah ilmiah dan juga dapat diaplikasikan di berbagai konteks pelabuhan yang berbeda. Metode evaluasi ini terdiri dari empat fase, yang terdiri dari (1) Analisis sistem pelabuhan dan konektivitas pulau; (2) Analisis kurva ketahanan pelabuhan; (3) Analisis dampak bencana; dan (4) Analisis intervensi ketahanan pelabuhan. Tiga studi kasus yang digunakan, antara lain di Pelabuhan Pantoloan, Pelabuhan Seba, dan Pelabuhan Mamuju menunjukkan bahwa keempat fase dapat diaplikasikan dengan baik di ketiga pelabuhan tersebut. Hasil dari analisis pada setiap fase kemudian disintesis untuk memberikan berbagai pembelajaran untuk penguatan ketahanan pelabuhan di masa yang akan datang.

Satu pelajaran penting dari pengembangan dan proses implementasi metode evaluasi ketahanan pelabuhan ini adalah metode ini sangat bergantung pada data (*data-driven method*). Dengan kata lain, objek studi yang tidak memiliki ketersediaan data yang lengkap dan akurat untuk melakukan analisis di empat fase tersebut akan mengalami kendala dalam menggunakan metode ini. Aplikasi metode ini pada studi kasus pelabuhan yang tidak memiliki data lengkap menunjukkan betapa proses implementasi menjadi suatu hal yang menantang dan menghabiskan banyak waktu. Hal ini menyiratkan bahwa untuk dapat mengevaluasi ketahanan pelabuhan bukan hanya dibutuhkan metode yang terstruktur dan ilmiah, namun juga keberadaan data untuk dianalisis.

Untuk evaluasi pelabuhan umum secara pragmatis, studi ini merekomendasikan pelabuhan – pelabuhan di seluruh dunia untuk mulai mengumpulkan data – data yang memudahkan analisis pada fase 2 dan fase 4, karena dua fase tersebut merupakan fase inti dalam melakukan evaluasi ketahanan pelabuhan. Sementara untuk pelabuhan – pelabuhan di negara kepulauan, selain fase 2 dan 4, perlu menyiapkan infrastruktur atau prosedur untuk bagaimana memiliki data yang lengkap dan akurat dalam memudahkan analisis di fase 1 dan 3 yang juga mempertimbangkan aspek spasial kepulauan dalam melakukan evaluasi ketahanan pelabuhan. Melalui evaluasi ketahanan pelabuhan yang ilmiah dan terstruktur yang dihasilkan dalam studi ini, pemangku kepentingan pelabuhan baik di negara kepulauan dan non-kepulauan dapat mengevaluasi ketahanan pelabuhan mereka secara mandiri. Adapun hasil dari evaluasi tersebut dapat dikumpulkan dan menjadi pengetahuan kolektif untuk meningkatkan ketahanan pelabuhan di negara – negara kepulauan seluruh dunia. Metode ini dan turunannya nanti juga dapat digunakan untuk melengkapi bagian yang hilang dalam panduan Perserikatan Bangsa Bangsa dalam mengembangkan kapasitas ketahanan pelabuhan di masa yang akan datang (UNCTAD, 2022).

Samenvatting

Achtergrond

Havens zijn essentieel voor het verkeer van goederen en mensen in eilandstaten. Een operationeel verstoorde haven kan de stroom van goederen en mensen verstoren, waardoor gemeenschappen op het eiland geïsoleerd raken. Natuurlijke en menselijke factoren kunnen deze operationele verstoring veroorzaken. Gezien de belangrijke rol van de haven neemt de verstoring van havenactiviteiten door natuurrampen toe. De opwarming van de aarde en de klimaatverandering vergroten het risico dat havens operationele verstoringen ondervinden door klimatologische risico's, zoals zware regenbuien, overstromingen en tropische cyclonen. Voor archipellanden zoals Indonesië gaat dit gepaard met risico's door geologische gevaren zoals aardbevingen, tsunami's en vulkaanuitbarstingen. Dit verhoogde risico betekent dat de aanpak niet langer preventief is, maar ook responsief wanneer een haven in een archipel wordt getroffen door een ramp. De opkomende theorie van havenbestendigheid, die kan worden gedefinieerd als het vermogen om terug te keren naar de oorspronkelijke prestaties nadat het is getroffen door een verstoring, is dus essentieel om te worden aangenomen zodat havens in eilandlanden een hoge operationele veerkracht hebben om het vervoer van goederen en mensen tussen eilanden te ondersteunen.

Dit onderzoek is een poging om de veerkracht van havens in archipellanden bij natuurrampen te verbeteren, vooral in grootschalige archipellanden zoals Indonesië. Indonesië is een archipel met een hoog risico op natuurrampen, zowel klimaatverandering als geologische rampen. Volgens de Verenigde Naties (2022) is een van de inspanningen om de veerkracht van havens te verbeteren het leren van de evaluatie van de ervaringen van eerdere incidenten met havenverstoringen. Deze evaluaties zullen naar verwachting lessen opleveren met betrekking tot succesverhalen, lessen uit mislukkingen en de effectiviteit van strategieën die worden gebruikt om de veerkracht van havens te verbeteren.

Helaas is er geen bestaande gestructureerde en wetenschappelijke methode die dergelijke incidenten objectief kan evalueren. Bestaand onderzoek in de literatuur over de veerkracht van havens is voornamelijk gericht op mitigatie-inspanningen en *ex-ante* analyses om het niveau van de veerkracht van havens in te schatten wanneer ze worden getroffen door natuurrampscenario's. De afwezigheid van een gestructureerde en wetenschappelijke methode om *ex-post* analyses uit te voeren van incidenten die havenactiviteiten verstoren, motiveerde en stimuleerde dit onderzoek. Het hoofddoel van dit onderzoek is het ontwikkelen van een wetenschappelijke en gestructureerde methode om belanghebbenden in havens, vooral in de archipel, te helpen bij het evalueren van hun operationele veerkracht bij natuurrampen.

Onderzoeksvraag en focus

De belangrijkste onderzoeksvragen van dit proefschrift zijn als volgt:

Hoe kan de veerkracht van havens bij natuurrampen in de archipel worden geëvalueerd?

Om dit te bereiken consolideert dit onderzoek de definitie en het concept van havenweerbaarheid. Zodra de definitie en het idee van havenweerbaarheid zijn geconsolideerd, is de volgende stap het formuleren van hoe het idee kan worden geoperationaliseerd, zodat het kan worden gebruikt om havenweerbaarheid te evalueren nadat het is getroffen door natuurrampen in de echte wereld. Nadat het concept van havenweerbaarheid kan worden geoperationaliseerd, gaat dit onderzoek verder met het ontwikkelen van een wetenschappelijke en gestructureerde methode voor het evalueren van havenweerbaarheid in de archipel door middel van vier fasen.

Formele richtlijnen voor het ontwikkelen van evaluatiemethoden

De volgende stap in het ontwikkelen van de methode was het bestuderen van bestaande benaderingen voor het ontwikkelen van methoden voor het analyseren en oplossen van problemen. Dit onderzoek nam de formele richtlijnen over van McMeekin et al. (2020), die een uitgebreide studie uitvoerden waarin de literatuur werd onderzocht en samengevat bij het creëren van methodologische kaders, gedefinieerd als een verzameling praktische en systematische richtlijnen voor het uitvoeren van een bepaald proces. Op basis van de synthese van deze formele richtlijnen kent dit onderzoek vier fasen in het ontwikkelen van een methode voor het evalueren van de veerkracht van havens. De vier stappen zijn: (1) het bestuderen van de literatuur om het theoretische basiskader voor het ontwikkelen van de methode te vinden; (2) het ontwikkelen van de evaluatiemethode op basis van het gegenereerde theoretische kader; (3) het testen van de evaluatiemethode aan de hand van praktijkcases; en (4) het reflecteren op de evaluatieresultaten om de generaliseerbaarheid van de ontwikkelde methode te bepalen.

Theoretisch kader voor de ontwikkeling van de methode

De eerste theoretische basis van dit onderzoek is de literatuur over het begrip veerkracht in haveninfrastructuur. De resultaten van het literatuuronderzoek tonen aan dat er drie perspectieven zijn bij het bekijken van havenbestendigheid, namelijk: (1) havenbestendigheid als het vermogen om de impact van rampen te weerstaan; (2) havenbestendigheid als het vermogen om te reageren op ervaren rampen; en (3) havenbestendigheid als het vermogen om aan te geven hoe snel de haven terugkeert naar zijn oorspronkelijke prestaties. De drie bovenstaande perspectieven worden vervolgens gecombineerd en geconceptualiseerd met behulp van een veerkrachtcurve. Daarna wordt het concept havenbestendigheid geoperationaliseerd door attributen van havenbestendigheid te identificeren in de literatuur, zoals: robuustheid van de haven, kwetsbaarheid, reactievermogen, snelheid en herstelvermogen om havenbestendigheid te meten op basis van deze drie perspectieven.

De tweede theoretische basis die gebruikt is bij het ontwikkelen van de methode in dit onderzoek is de literatuur over de kenmerken van een archipel gezien vanuit de onderlinge relatie tussen eilanden in het land. Op basis van de resultaten van het literatuuronderzoek werd vastgesteld dat eilanden in een archipel moeten worden gezien als een entiteit die met elkaar verbonden is, ook wel *eilandrelationaliteiten genoemd. Volgens* het economisch model *kern-periferie* zal in een archipel een eiland altijd de belangrijkste economische motor zijn (*kern*) en zullen de omliggende eilanden afhankelijk zijn van het kerneiland (*periferie*). Havens zijn de belangrijkste toegangspoorten die de creatie van deze eilandrelatie mogelijk maken. Gebaseerd op deze visie worden havens in eilandlanden gezien als elkaar ondersteunend, samenwerkend om te voldoen aan de behoeften van de gemeenschap met betrekking tot het verkeer van mensen en goederen in plaats van concurrerend zaken te doen. Havens in archipellanden moeten worden gezien als elkaar ondersteunend, samenwerkend om te voldoen aan de behoeften van de gemeenschap met betrekking tot het verkeer van mensen en goederen, in plaats van met elkaar te concurreren op het gebied van zakendoen. Bij de evaluatie van de veerkracht van havens in een archipel moet dus niet alleen worden gekeken naar de interne omstandigheden van de verstoorde haven, maar moet de haven ook worden gezien als een entiteit die deel uitmaakt van een complex havennetwerk, in plaats van alleen als een onafhankelijke entiteit.

De derde theoretische basis voor het ontwikkelen van deze methode is de literatuur die de complexiteit van havenoperaties in een archipel laat zien door rekening te houden met de relatie tussen eilanden. Gezien de relatie tussen de eilanden bestaat de complexiteit van de operationele analyse in een archipel uit ten minste drie lagen van analyse. De eerste laag is de analyse op het havenniveau zelf, die zich richt op hoe de sociale en technische componenten van de haven op elkaar inwerken om de verwachte havenactiviteiten te produceren. De haven wordt daarom gezien als een complex *socio-technisch* systeem. De tweede laag is een analyse van de verbanden tussen havens en andere alternatieve havens op hetzelfde eiland. Deze koppeling wordt meestal voorgesteld door de beschikbaarheid van transportinfrastructuur over land die deze havens met elkaar verbindt, over de weg of per spoor. Dit is belangrijk gezien de over het algemeen coöperatieve aard van havens in archipellanden, zodat het niveau van havenweerbaarheid kan worden beïnvloed door het vermogen van alternatieve havens op het eiland om middelen of reservecapaciteit te delen om de verloren capaciteit van de getroffen haven te vervangen. De derde laag is de analyse van de connectiviteit tussen het getroffen eiland en andere eilanden die door de haven worden verbonden. De isolatie van een eiland kan het veerkrachtniveau van de haven op het eiland beïnvloeden, vooral als er externe bronnen van andere eilanden nodig zijn om de prestaties van de haven te herstellen.

De bovenstaande drie theoretische fundamenten worden gebruikt om een methode te ontwerpen voor het evalueren van de veerkracht van havens in archipellanden. Het XLRM-diagram werd vervolgens gebruikt om de resultaten van het literatuuronderzoek te structureren in een theoretisch kader. Het XLRM-diagram vertegenwoordigt exogene onzekerheden (X), beleidshefbomen (L), systeemrelaties (R) en prestatiemetingen (M). Met behulp van XLRM werden de resultaten van het literatuuronderzoek vervolgens gekaderd als een heel systeem dat moest worden geanalyseerd binnen de beperkingen van de vier hoofdcomponenten als theoretisch kader voor het ontwikkelen van methoden om de veerkracht van havens te evalueren.

Ontwikkeling van de evaluatiemethode op basis van het theoretisch kader

Op basis van het theoretisch kader werd in dit onderzoek een evaluatiemethode ontwikkeld voor de veerkracht van havens in insulaire landen in vier hoofdfasen. De eerste fase is de analyse van havensystemen en eilandconnectiviteit. De **eerste fase** operationaliseert het theoretische kader van systeemrelaties (R). Het doel van de eerste fase is om de context van het geanalyseerde systeem te begrijpen. De resultaten van deze analyse kunnen worden gebruikt om te bepalen of er een verband is tussen havenweerbaarheid en de havencontext. Er zijn drie soorten analyses die in deze fase worden uitgevoerd, namelijk (1) analyse van havenactiviteiten als een socio-technisch systeem, (2) analyse van havenconnectiviteit met andere alternatieve havens op hetzelfde eiland, en (3) analyse van havenconnectiviteit met havens op andere eilanden, wat de operationalisering is van *eilandrelationaliteiten.*

De **tweede fase van** de evaluatiemethode is de analyse van de havenweerstandscurve. Deze analyse operationaliseert het theoretische kader van prestatiemeting (M). De metriek voor het meten van havenprestaties wordt eerst bepaald om de veerkrachtcurve van de haven te construeren. Zodra de metrieken zijn gespecificeerd, wordt de prestatie van de haven in de loop van de tijd gemeten gedurende één volledige havenweerstandscyclus. Eén cyclus omvat ervoor, tijdens en erna totdat de havenprestaties weer normaal zijn. Nadat de veerkrachtcurve van de haven is gevormd, is de volgende stap het meten van de veerkrachtprestatie door het berekenen van het niveau van *robuustheid, kwetsbaarheid, reactievermogen, snelheid* en *herstelbaarheid* op basis van de gevormde curve. Deze tweede fase is de kern van de evaluatie omdat verdere analyse kan worden gedaan nadat deze tweede fase is voltooid.

De **derde fase van** deze evaluatiemethode is de rampenimpactanalyse. De rampenimpactanalyse is een operationalisering van het theoretische kader van hoe exogene onzekerheid (X), vertegenwoordigd door natuurrampen, de conditie van de systeemrelatie (R) beïnvloedt. De analyse in deze fase richt zich op het onderzoeken van de mate waarin natuurrampen van invloed zijn op de veerkracht van havens en eilandrelaties. In deze fase worden de drie soorten analyses opnieuw uitgevoerd, net als in de eerste fase, maar het onderzoek wordt uitgevoerd nadat de ramp de haven heeft getroffen. Deze derde fase is erop gericht om te bepalen in hoeverre een ramp invloed heeft gehad op de haveninfrastructuur en de eilandrelaties die door de ramp zijn getroffen.

De **vierde fase van** deze evaluatiemethode is de analyse van interventies of strategieën die zijn genomen om de veerkracht van havens bij natuurrampen te verbeteren. Deze analyse bestaat uit vier tijdsbestekken gebaseerd op de tijdsindeling op de havenweerstandscurve. De resultaten van deze vierde fase zullen naar verwachting lessen opleveren met betrekking tot welke interventies al dan niet effectief zijn om de veerkracht van havens bij natuurrampen te vergroten. De analyseresultaten van deze vier fasen worden vervolgens samengevoegd om lessen te trekken die hopelijk de veerkracht van de betreffende haven in de toekomst of de veerkracht van andere havens met een vergelijkbare context kunnen vergroten.

Toepassing van de evaluatiemethode op praktijkcasussen

In dit onderzoek is de methode getest op drie praktijkcasestudies. De drie casestudies zijn geselecteerd uit Indonesië, een archipel met veel eilanden, havens en risico's op natuurrampen die van invloed kunnen zijn op de havenactiviteiten. De casestudies die in dit onderzoek zijn gebruikt, zijn de volgende:

Casestudie 1: *Pantoloan-haven na aardbeving en tsunami in Centraal-Sulawesi (2018)*

De eerste toepassing van deze methode is het evalueren van de veerkracht van de haven van Pantoloan toen de havenactiviteiten werden verstoord door de aardbeving en tsunami van 2018. In deze casestudie vertegenwoordigt de haven van Pantoloan de implementatie van de methode in een grote haven in Indonesië, waar containers worden geladen en gelost, die commercieel is en een belangrijke haven in de hiërarchie van zeehavens in Indonesië. Bovendien vertegenwoordigt het incident van 28 september 2018 het implementatieproces in de context van een geologische ramp, meer bepaald een aardbeving en tsunami van 7,5 Mw.

De vier fasen van de evaluatiemethode voor havenweerbaarheid werden met succes toegepast op de casestudycontext van de Pantoloan Port. De resultaten van de evaluatie van de veerkracht van de haven met behulp van de havenweerstandscurve laten zien dat de haven van Pantoloan 296 dagen nodig heeft om de prestaties na de ramp te herstellen naar de normale havenprestaties van voor de ramp. De verschillende gegevens en het implementatieproces van elk van de vier fasen van deze methode worden meer volledig en in detail uitgelegd in hoofdstuk 4. Het hoofdstuk beschrijft ook verschillende geleerde lessen die kunnen worden genomen om de veerkracht van Pantoloan Port te verbeteren, met name in de toekomst of andere havens in het algemeen die kenmerken hebben die vergelijkbaar zijn met Pantoloan Port afgeleid van de implementatie van de vier fasen evaluatiemethode.

Casestudie 2: *Haven van Seba na tropische cycloon Seroja in 2021*

De tweede toepassing van deze methode is het evalueren van de veerkracht van de haven van Seba, gelegen op Sabu Island, een klein eiland in de provincie Oost-Nusa Tenggara, toen de havenactiviteiten werden verstoord door het incident van de tropische cycloon Seroja in 2021. Deze casestudy biedt een voorbeeld dat naar verwachting representatief is voor een kleine haven, ver van het hoofdeiland, die een niet-commerciële openbare haven is en het vervoer van niet-gecontaineriseerde goederen op Sabu-eiland verzorgt. Het incident, dat plaatsvond op 6 april 2021, vertegenwoordigt ook het implementatieproces van de methode op een meteorologische ramp, in het bijzonder de 102 km/u tropische cycloonwinden die de haven troffen.

Dit casestudieresultaat toont aan dat de implementatie van alle vier fasen van de evaluatiemethode van de veerkracht van de haven in Seba Port goed kan worden toegepast ondanks de beperkte beschikbaarheid van openbare gegevens. De resultaten van de evaluatie van de veerkracht met behulp van de havenweerstandscurve toonden aan dat de haven van Seba 261 dagen nodig had om terug te keren naar de normale havenprestaties sinds de impact van cycloon Seroja. De gebruikte gegevens en het proces van het implementeren van de vier fasen van de evaluatiemethode worden uitgebreider beschreven in hoofdstuk 5. De analyseresultaten van de vier fasen worden vervolgens gebruikt om waardevolle lessen te trekken die kunnen worden gebruikt om de veerkracht van de haven van Seba in de toekomst of andere havens met een vergelijkbare context als de haven van Seba te verbeteren.

Casestudie 3: *Mamuju Simboro haven na de aardbeving in Majene in 2021*

De derde toepassing van deze methode is het evalueren van de veerkracht van Mamuju Simboro Port in West Sulawesi, waarvan de activiteiten werden getroffen door de 6,2 Mw West Sulawesi Aardbeving op 15 januari 2021. Deze casestudie biedt een voorbeeld voor het implementeren van de methode in een middelgrote haven met passagiersschepen en een commerciële haven, die andere kenmerken heeft dan de vorige twee havens. Deze casestudie geeft ook het implementatieproces weer in de context van een geologische ramp, meer bepaald een aardbeving van 6,2 Mw.

Deze casestudy laat zien dat het implementeren van alle vier de fasen van de evaluatiemethode voor havenweerbaarheid in de haven van Mamuju haalbaar is, ondanks de beperkte beschikbaarheid van openbare gegevens en de moeilijke toegang tot primaire gegevens. De resultaten van de evaluatie van de veerkracht met behulp van de havenweerstandscurve laten zien dat het 427 dagen duurt voordat de haven weer normaal functioneert na door de ramp te zijn getroffen. De analyseresultaten van de vier fasen worden vervolgens gebruikt om lessen en inzichten te trekken die de basis kunnen vormen voor het versterken van de veerkracht van Mamuju Simboro Port in de toekomst of andere havens die vergelijkbaar zijn met Mamuju Simboro Port.

Reflectie op de resultaten en generalisatie van de methode

Op basis van het proces en de resultaten van de methodeimplementatie in de drie casestudies kan worden vastgesteld dat de methode met succes is toegepast en de verwachte analyse-output heeft opgeleverd. Wat zijn de implicaties van het succesvolle gebruik van de methode voor de drie casestudies? Als archipel heeft Indonesië ongeveer 3.224 havens die de eilandconnectiviteit en onderlinge verbondenheid ondersteunen. Van het totale aantal havens is 81% van de havens vergelijkbaar met of vertegenwoordigd in de drie casestudies. Op basis van de resultaten van dit onderzoek is deze methode dus vrij flexibel en kan ze worden gebruikt voor 81% van de havens in Indonesië die een vergelijkbare context of vergelijkbare kenmerken hebben als de drie casestudy's, op voorwaarde dat de gegevens die nodig zijn om de analyse uit te voeren beschikbaar, volledig en toegankelijk zijn. De resultaten van het implementatieproces laten zien dat als er meer gegevens nodig zijn of als het moeilijk is om toegang te krijgen tot de benodigde gegevens, deze methode erg complex, ingewikkeld en tijdrovend wordt. Verder onderzoek kan worden gedaan om de effectiviteit van deze methode te testen op havenactiviteiten die in de 81% karakteristieke categorie vallen, maar een zeer extreme havengrootte hebben, of het nu een te grote of een kleine haven is.

Voor de generalisatie en het gebruik van deze methode naar havens in andere archipellanden dan Indonesië, kan eerst worden nagegaan of de havengrootte, de ramp en het eiland die moeten worden geëvalueerd vergelijkbare kenmerken hebben als de casestudy die in dit onderzoek wordt geïllustreerd. Stel dat er veel vergelijkbare kenmerken zijn tussen de drie aspecten. In dat geval kan de toepassing van de methode direct worden gevolgd door wat in deze studie is beschreven in de hoofdstukken 4 tot en met 6. Deze methode is zeer flexibel en kan worden gebruikt in de context van de meeste havens in een grootschalige archipel. De kwaliteit en beschikbaarheid van de gegevens die nodig zijn voor de analyse zijn echter ook cruciaal voor een succesvol gebruik van deze methode. Dit zal het bewustzijn van havenstakeholders in de archipel vergroten, zodat ze kunnen beginnen met het voorbereiden van de gegevens die nodig zijn om de veerkracht van havens op de juiste manier te evalueren. Voorbeelden van de vereiste gegevens zoals beschreven in deze studie kunnen een weg banen voor wat betreft de soorten gegevens die vanaf nu met voorrang moeten worden verzameld, zodat het evaluatieproces van de veerkracht van de haven gemakkelijker en sneller kan worden uitgevoerd.

Wat betreft het gebruik van deze methode in havens met operationele kenmerken buiten de casestudy, is verder onderzoek nodig, afhankelijk van de context van de haven die wordt geëvalueerd. Nog eens 19% van de havens in Indonesië zijn bijvoorbeeld gespecialiseerde havens met zeer gespecialiseerde havenfuncties. Voorbeelden hiervan zijn havens of terminals die gespecialiseerd zijn in het laden en lossen van grondstoffen of afgewerkte goederen in de plantage-, veeteelt-, visserij-, mijnbouw-, landbouw- of bosbouwindustrie. Elk van deze havens heeft zeer specifieke operationele kenmerken, dus het toepassen van deze methode zal waarschijnlijk aanpassingen in het proces vereisen. Daarom moeten de fasen die zijn voorbereid en de analyse-instrumenten in deze methode worden herzien om te bepalen of ze geschikt zijn voor het type haven dat wordt bestudeerd en of de vereiste gegevens kwalitatief en kwantitatief beschikbaar zijn.

Conclusie

Dit proefschrift en onderzoek zijn opgezet om een wetenschappelijke en gestructureerde methode te ontwikkelen om belanghebbenden bij havens in eilandnaties te helpen bij het evalueren van de veerkracht van hun havens bij natuurrampen die al hebben plaatsgevonden (*ex-post analyse*). De belangrijkste uitdagingen bij het creëren van een uitgebreide maar praktisch toepasbare methode zijn de complexiteit van archipelstaten die bestaan uit onderling verbonden eilanden (*eilandrelaties*), de complexiteit van havens als *socio-technische* systemen en inconsistente definities en concepten van havenweerbaarheid tegen natuurrampen. Deze studie richt zich op het ontwikkelen van een methode met deze drie overwegingen in het achterhoofd, waarbij andere beïnvloedende factoren buiten het bereik van deze studie vallen.

De algemene conclusie is dat de evaluatiemethode voor havenweerbaarheid in vier fasen van deze studie voldoet aan wetenschappelijke principes en ook kan worden toegepast in verschillende havencontexten. Deze evaluatiemethode bestaat uit vier fasen: (1) analyse van het havensysteem en eilandconnectiviteit, (2) analyse van de havenweerstandscurve, (3) rampenimpactanalyse en (4) analyse van de havenweerbaarheidsinterventie. De drie casestudies, Pantoloan Port, Seba Port en Mamuju Port, laten zien dat de vier fasen goed kunnen worden toegepast in de drie havens. De analyseresultaten van elke fase werden vervolgens samengevoegd om verschillende lessen te bieden voor toekomstige versterking van de veerkracht van havens.

Een belangrijke les uit het ontwikkelings- en implementatieproces van deze evaluatiemethode voor havenbestendigheid is dat het een gegevensafhankelijke methode is. Met andere woorden, het bestuderen van objecten zonder volledige en nauwkeurige gegevens om de vier fasen te analyseren zal obstakels veroorzaken bij het gebruik van deze methode. Het toepassen van deze methode op een havencasestudy zonder volledige gegevens laat zien hoe uitdagend en tijdrovend het implementatieproces kan zijn. Dit betekent dat het evalueren van de veerkracht van havens niet alleen een gestructureerde en wetenschappelijke methode vereist, maar ook het bestaan van gegevens om te analyseren. Voor een pragmatische evaluatie van publieke havens beveelt dit onderzoek aan dat havens wereldwijd beginnen met het verzamelen van gegevens die de analyse in fase 2 en fase 4 vergemakkelijken, aangezien dit de kernfasen van de evaluatie van de veerkracht van havens zijn.

Ondertussen moeten havens in eilandlanden, naast fase 2 en 4, infrastructuur of procedures voorbereiden voor het hebben van volledige en nauwkeurige gegevens om de analyse in fase 1 en 3 te vergemakkelijken, waarbij ook rekening wordt gehouden met de ruimtelijke aspecten van de archipel bij het uitvoeren van evaluaties van de veerkracht van havens. Door middel van de wetenschappelijke en gestructureerde evaluatie van de veerkracht van havens die in dit onderzoek is geproduceerd, kunnen belanghebbenden in de havens in de eiland- en niet-eilandlanden onafhankelijk hun veerkracht van havens evalueren. De evaluatieresultaten kunnen worden verzameld en collectieve kennis worden om de veerkracht van havens in eilandstaten wereldwijd te verbeteren. Deze methode en zijn afgeleiden kunnen ook de ontbrekende stukken opvullen in de praktische richtlijnen van de Verenigde Naties (UNCTAD, 2022) over het verbeteren van de veerkracht van havens.

Content

1 Introduction

Ports are one of archipelagic countries' most important infrastructures for inter-island transportation. The availability of adequate port facilities can support the smooth movement of goods and passenger flows that can support economic growth and prevent the isolation of islands in the country. Given this role's importance, ports are experiencing increasing levels of disruption. Causes of disruption such as climate change, natural disasters, and operational accidents make ports vulnerable because these risks are increasingly inevitable in the future. Especially in archipelagic countries, ports that are not resilient will increase the risk of isolation of islands, making many people on an island unable to access their primary needs or move to a place that can hamper social welfare and economic activity.

One way to enhance port resilience capacity is to learn from the resilience of ports disrupted in the past. In this context, a comprehensive review, known as the *review phase* (a term adapted from the United Nations' approach to building port resilience) after a port has been disrupted can be seen as an opportunity to evaluate how resilient a port is and the effectiveness of response or mitigation strategies, which affect resilience. Identified successful strategies to enhance port resilience can enrich the current literature so that other ports can learn from best practices. In addition, ineffective strategies or obstacles can also be valuable lessons so that they are not repeated in the future.

Unfortunately, a scientific, structured, yet practical method for conducting such port resilience evaluation activities did not exist when this research was initiated. One of the biggest challenges in creating this method is the concept of port resilience itself, which is still vague due to fragmented understanding in the scientific literature. The inconsistency in conceptualizing what port resilience is will impact the difficulty of operationalizing the concept of resilience to evaluate port resilience in the past. This dissertation focuses on developing methods that can be used to evaluate port resiliencse after a disruptive event based on scientific theories developed in the current literature. More specifically, this dissertation attempts to consolidate the scientific theoretical foundation of port resilience and proposes a method to review port resilience in the archipelago (hereafter, we use the term 'evaluation') based on that theoretical foundation. This chapter will further explain what we mean by this and why it is important to study.

1.1 Background and motivation

Maritime ports are critical in archipelago nations' connectivity and economic development (Luis, 2002; Makkonen et al., 2013; Sandee, 2016). This is due to the dispersed distribution of inhabited islands, which are often divided into main and remote islands, resulting in a heavy dependence on maritime transport for the movement of goods and people (Kusuma & Tseng, 2019). In main islands, ports serve as hubs for domestic and international trade, facilitating the import and export of goods. In remote islands, ports are often used as feeders to connect isolated islands in the regions to main islands through established maritime transport networks (Collins & Diansari, 2018). Maritime transport is frequently considered the primary mode of transportation for island communities, as it is typically less expensive than air transport and beneficial for those relying on inter-island mobility and imported goods from main islands (Park et al., 2019; Stopford, 2009). Consequently, the availability and reliability of port services in the archipelago are crucial to maintaining the flow of goods, services, and people between islands, promoting economic growth and social development in the region (Hayakawa et al., 2020).

Natural disasters can threaten and disrupt port operations despite the significance of reliable port services for island communities (Verschuur et al., 2020). An empirical study conducted by Verschuur et al. (2023) found that 86% majority of ports globally are exposed to more than three natural hazards, which underlines that most ports pose the challenge of multiple types of natural disasters. The most common types of natural disasters that affected ports worldwide were tropical cyclones, storms, and coastal flooding, followed by earthquakes and tsunamis that most likely occur and impact ports in the archipelago (Andrade et al., 2006; Caselli et al., 2014). Small Island Developing States (SIDS) and archipelagic nations, whose economies are critically dependent on maritime transport, face a disproportionately high risk of maritime trade-flow disruptions caused by port shutdowns due to natural disasters. This risk is estimated to be 3.7 times higher than non-islands and archipelago economies (Verschuur et al., 2023).

Several scientific evidence explain why the islands and archipelago ports have a higher risk of natural disasters. A study by Izaguirre et al. (2020) mentioned that archipelago and island ports located in the Pacific Ring of Fire, such as Indonesia, the Philippines, and Japan, are projected to have a very high risk of climatological disaster in 2100 under the Representative Concentration Pathway 8.5 (RCP8.5) scenario. RCP8.5 scenario assumes high future emissions with a dramatic expansion of coal use, frequently referred to as "business as usual" if society does not make a concerted effort to cut greenhouse gas emissions (Schwalm et al., 2020). Not only climatological risk, Holden et al. (2017) argue that the rising trend of climate change will enhance geophysical hazards. Climate change will potentially reduce the thickness of the

Greenland and Antarctic ice sheets (Bellard et al., 2014). As the thickness of the ice sheets decreases, the weight being borne by the tectonic plates will be reduced, which could generate more tectonic activities. As a result, the overall frequency and severity of geological and climatological disasters that can lead to severe port disruptions or shutdowns are expected to increase substantially in the future (Djalante & Garschagen, 2017).

Port shutdowns due to natural disasters can profoundly impact the archipelagos' local population (Rose & Wei, 2013). It can obstruct the flow of goods, leading to wide-ranging effects on the regional economy. A study by Amin et al. (2021) found that disruptions to port efficiency caused by natural disasters in the eastern region of Indonesia had a significant negative impact on the movement of goods, resulting in higher logistics costs, increased commodity prices, and a reduction in Gross Regional Domestic Product per capita. Tourism and hospitality industries in the archipelagos can also be severely impacted by port disruptions (Lousada & Castanho, 2022). This is particularly significant as tourism is often a major source of income for island communities (Briguglio & Briguglio, 1996). Port shutdowns can also affect the social welfare of local populations in remote islands, which are often far from the mainland and have limited resources. When the port is closed, access to essential supplies such as food, fuel, and medical supplies can become challenging, posing serious risks to the health and well-being of the local population (Kim & Bui, 2019).

Given the increasing frequency and severity of natural disasters, the study of resilience has gained prominence in the context of port management in archipelagos (Kusuma & Tseng, 2019; Makkonen et al., 2013; Ralahalu & Jinca, 2013). The aim is to provide more reliable and accessible maritime transportation services to island communities. The term 'resilience' generally refers to the ability of a port to bounce back after its operations have been disrupted (Mansouri et al., 2010; Omer et al., 2012). This concept is emerging in recognition that traditional risk management approaches to mitigation are often inadequate, and increasingly, the conditions under which ports must accept and embrace the risk are unavoidable (Wang, 2015). For example, ports in the archipelago or inter-island countries often do not have the option to build ports on land that is the epicenter of earthquake faults because the island is located in an earthquake-prone area (Kensen, 2019). Meanwhile, earthquakes are very difficult to predict when they will come and how strong they will be. COVID-19 is another recent example that disrupted islands and non-island ports and raised awareness that ports must immediately consider port resilience to be adopted (UNCTAD, 2022). This makes resilience relevant to making ports on islands bounce back more quickly when experiencing natural disasters, in addition to traditional risk management concepts that are also important to consider (Yarveisy et al., 2020).

The importance of resilience in ports led the United Nations to publish a five-step approach to building port resilience (UNCTAD, 2022). The five steps are: (1) Identify Hazards, (2) Vulnerability and Impact Assessment, (3) Elaborate Response and Mitigation Options, (4) Prioritize Options, and (5) Implement and Review the Port Resilience as shown in Figure 1. These steps are used as formal guidance from the United Nations that can be used to improve port resilience and adapt to the context of the archipelagic port. If examined more closely, the first four steps of the approach focus on preparing the port before an event that can cause disruption. The fifth step (review) focuses on learning from ports that experience operational disruption after a disruptive event occurs.

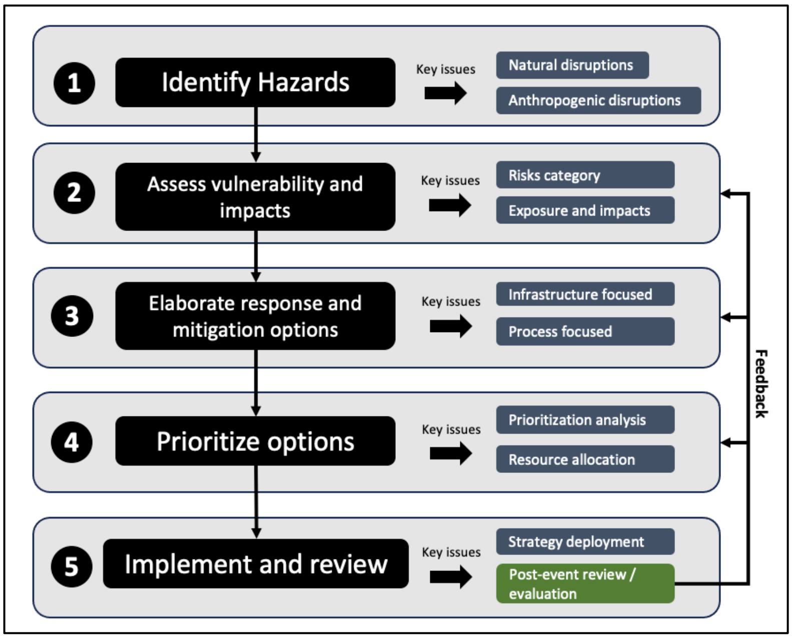

Figure 1. Formal guidance to enhance port resilience (adapted from UNCTAD, 2022)

The United Nations (2022) emphasizes the importance of systematically evaluating port resilience after disruptive events to enhance port resilience in the future. A port resilience evaluation process can standardize the process to measure their resilience after being affected by disruptive events and learn what effective and ineffective strategies affect the resilience level. In other words, a port resilience evaluation based on past events offers valuable insights into improving future port resilience, especially for ports with similar contexts and risks of disruptive events. These insights are especially needed by ports in island-based countries with unique characteristics (Destyanto et al., 2021), given the crucial role of ports in these countries and the lack of literature discussing lessons learned from port resilience evaluations in the same or similar contexts.

However, research on empirical port resilience evaluation is still in its early stages, and research to provide comprehensive, structured evaluation methods is lacking (Qin et al., 2023). Development of a scientific yet practical method for port resilience evaluation, especially in an archipelago context, remains limited. Most existing evaluation methods focus on evaluating a commercial port as an entity independent of its interrelationships with other ports, as it is assumed that commercial ports are economically competitive (Touzinsky et al., 2018; Qin et al., 2023; Verschuur et al., 2022). This means that current port resilience evaluations do not consider the port's role as a component of a larger shipping network. Meanwhile, evaluating resilience in an archipelago context poses several challenges and distinct characteristics.

First, resilience is a complex and multi-disciplinary idea, which leads to various interpretations when applied in the port context. The multi-interpretation of the resilience concept can hinder operationalization when evaluating port resilience, especially in the archipelago. Second, ports in the archipelago have diverse types and resilience capacities, which are influenced by their geographical location and their role in the maritime network

(Zheng et al., 2017; Destyanto et al., 2021). This indicates that the spatial factor of the island where the port is located must be considered when evaluating the port resilience. In other words, the resilience evaluation process for ports in the archipelago is constrained by the multi-interpretation of the concept of resilience and the different resilience capacities of each port due to differences in the spatial conditions of the island where the port is built. Third, the resilience of a port is often measured not only by the port's resilience but also by how resilient the *island's relationalities are* after port operations are disrupted.

This study tries to answer these challenges by proposing a method for evaluating port resilience to natural disasters in the archipelago based on a solid theoretical foundation of resilience and the spatial conditions of the archipelago, which have also not been widely explored in the scientific literature. The method can be adopted as the main reference for ports in small island states or large-scale archipelagos to evaluate port resilience after being affected by disasters. The results produced from the method can be used as lessons learned for ports that have similar contexts in (1) measuring the resilience level of ports affected by disasters that can be used as a benchmark or comparison and (2) knowing what strategies work and do not work in boosting port resilience levels.

The output results of implementing this method can later be compiled into a database that can be used as a lesson for other ports worldwide to build their future resilience. Other benefits expected from implementing this method are that it can be used as an empirical basis for simulation and modeling exercises, which can help estimate the resilience level of ports more accurately. This data can help validate and refine models and simulations of port resilience, providing a more accurate representation of the real-world complexities in an archipelago context.

1.2 Research objective and questions

This research aims to produce a method for evaluating port resilience to natural disasters in the archipelago that is systematic and practical yet based on a solid scientific foundation. To achieve the research objectives, this dissertation focuses on answering the following main research questions:

"How can port resilience to natural disasters in an archipelago be evaluated?"

The main research question can be addressed by answering the following sub-questions:

SQ 1. What key theoretical foundations can be adapted to evaluate port resilience to natural disasters?

SQ 2. How do the characteristics of ports in the archipelago affect the evaluation of resilience?

SQ 3. How can these theories of resilience and archipelago characteristics be framed and operationalized into a practical method for evaluating port resilience in an archipelago?

SQ 4. How can the proposed method be applied to different types of ports in an archipelago to evaluate their resilience?

SQ 5. What are the method's potentials beyond the case studies when applied to comparable or different ports?

To answer the above questions, this dissertation will use the Indonesian archipelago as the main case study to implement the method to evaluate port resilience. Indonesia was chosen as the central case study in this research because Indonesia is one of the world's largest archipelagos and has the highest inter-island complexity. In addition, the reason why Indonesia was chosen as the central case study is because Indonesia is located on the Pacific Ring of Fire, so Indonesia is prone not only to climatological disasters but also geological disasters such as earthquakes, tsunamis, and volcanic eruptions. Many ports have been affected by disasters in Indonesia, making Indonesia an appropriate case study object to test this port resilience evaluation method.

1.3 Research approach

A research approach is developed to establish a link between research questions and conclusions. First, we present the philosophical foundation underpinning the research, including its justification, is presented. Subsequently, the research design employed in this study is discussed.

1.3.1 Philosophical foundation

This section elaborates on the research paradigm adopted in this study to answer the research questions. According to Kuhn (1962), a research paradigm is a "set of common beliefs and agreements" researchers share regarding how problems should be understood and addressed. Therefore, the research paradigm explains how to perceive the world in a specific way, shaping the pursuit of answers to the research questions. Guba (1990) argued that ontological and epistemological dispositions mainly characterize a research paradigm. Ontology is an area of philosophy that concerns identifying the general nature of the existence of a particular phenomenon, while epistemology is an area of philosophy concerned with creating knowledge, focusing on how knowledge is obtained, and investigating the most proper ways to reach the truth. In other words, ontology is the nature of perceiving reality by answering the "*What is reality?*" question, and epistemology essentially determines the answer to the "*How do I know the reality?*" question.

The research paradigm adopted in a study determines the researcher's ontology and epistemology, shaping their approach to answer the research questions. There are three common research paradigms: positivism, interpretivism, and pragmatism. The positivism paradigm follows a realist ontology, which means that reality and things in the world have an objective existence independent of the researcher (Danermark, 2002). Positivists believe there is a single objective reality to any situation, regardless of the researcher's perspective or beliefs (Hudson & Ozanne, 1988). Consequently, positivists take a controlled and structured approach to research by identifying a precise research topic and appropriate hypotheses and adopting suitable research methods to prove the hypotheses. Quantitative research methods, such as descriptive statistics, correlational, causal-comparative, and experimental research, become central to positivist research as they are essential to seeking objective reality. The ultimate goal of a positivist is to produce knowledge that has time and context-free generalization.

In contrast to positivists, interpretivists believe that reality is relative and inseparable from human belief or experience (Bernard, 2013). The knowledge acquired in this paradigm is socially constructed rather than objectively determined. Consequently, interpretivism avoids rigid quantitative approaches and adopts more qualitative methods, such as historical research, in-depth case studies, or narrative research. To this end, interpretivism aims to interpret the meanings in human behavior rather than generalize and predict a phenomenon's exact causes and effects.

Unlike positivists and interpretivists, pragmatists accept that single or multiple realities can be open to empirical inquiry (Creswell, 2017). Pragmatists reject the traditional philosophical dualism of objectivity and subjectivity, allowing the researcher to avoid the dichotomy of positivism and interpretivism (Biesta, 2010). For pragmatists, objective reality and knowledge exist apart from the observer. However, reality is knowable through research that is affected by theoretical presuppositions and experiences the researcher holds to achieve the research objectives (Goles & Hirschheim, 2000; Morgan, 2014). Table 1 shows more detailed differences in positivism, interpretivism, and pragmatism research paradigms.

Pragmatism is predominantly present in this study. There are two reasons why pragmatism is becoming our predominant research paradigm. First, the ultimate goal of this study orients toward bridging the theoretical concept to be used for practical problem solving, which is supporting port management and transport authorities in archipelago nations to evaluate resilience to past natural disaster events for obtaining valuable lessons. In this case, pragmatism fits as a paradigm of inquiry for more practical-minded researchers. Second, this paradigm emphasizes the importance of collaboration between researchers and practitioners, leading to more relevant and impactful research. This paradigm allows for a more flexible and adaptive research process. As a result, it allows for considering multiple perspectives and the potential for improvement in answering the research questions.

Table 1. The differences between positivism, interpretivism, and pragmatism research paradigm

Disposition	Positivism	Interpretivism	Pragmatism
Ontology			
Nature of the world	Objective and independent of the researcher	Subjective and dependent of the researcher	Constantly changing and dynamic place
Reality	There is a single reality	There is no single objective reality	Reality is what works in solving real-world problems
Epistemology			
Grounds of producing knowledge	Possible to obtain and secure objective knowledge	Understood through 'perceived' knowledge	Emphasize on the usefulness and practicality of knowledge
Research goal	Establish objective, universal laws and principles	Understand subjective meanings and perspectives of individuals / groups	Solve problems through the application of knowledge
Knowledge generated	Objective, absolute, universal (time dan context-free)	Relative and multiple meanings (time and context-bound)	Useful, workable, practical (adaptable to time and context)
Methodology			
Research purpose	Concentrates on description and explanation	Concentrates on understanding and interpretation	Concentrates on solving problem through the application of knowledge
Research instruments or techniques used	Formalized statistical, mathematical, and quantitative methods predominant	Primarily non-quantitative (qualitative) instruments	Combination of quantitative and qualitative research instruments

1.3.2 Research formal guidance

The main objective of this research is to produce a method that can effectively evaluate the resilience of ports in the archipelago. While there is no explicit definition of a “method”, there is an implicit agreement in port and maritime literature that it “*provides systematic practical guidance or a tool for navigating a process*.” In other words, the method is defined as a set of structured principles, stages, or step-by-step phases to address a problem (Gajjar, 2016; Ivey et al., 2010; Mansouri et al., 2010; Nair et al., 2010; Ng & Pallis, 2010; Omer et al., 2012). In this study, the problem is the difficulty in evaluating port resilience. In this thesis and beyond, “*evaluation method*” and “*method*” are often used interchangeably.

By using the abovementioned definition, formal guidance is needed to facilitate the development of a research design for producing the method. This research adopts a formal guidance proposed by McMeekin et al. (2020). The reason for this adoption is because the research by McMeekin et al. (2020) comprehensively reviews and synthesizes how a methodological framework can be created. Secondly, the definition of methodological framework used is similar to the method definition in maritime literature.

McMeekin et al. (2020) synthesize a comprehensive literature review on how the methodological framework was produced in the existing literature. Their development process is broadly divided into three phases: (1) identifying evidence to inform the framework, (2) developing the framework, and (3) validating, testing, and refining the framework. This study splits the third phase into two phases to separate the testing activities and the further reflection. Adapting the procedure from McMeekin et al. (2020), there are four steps adopted in this study to produce the method: (1) reviewing the literature to construct a theoretical framework as scientific guidance in developing an evaluation method; (2) developing the practical method for evaluating port resilience based on the theoretical framework; (3) testing the evaluation method in real-world case studies; and (4) reflecting on the evaluation results to determine the generalizability of the developed method. Figure 2 shows an overview of the formal guidance in developing the method, which consists of four work steps adapted from McMeeking et al. (2020).

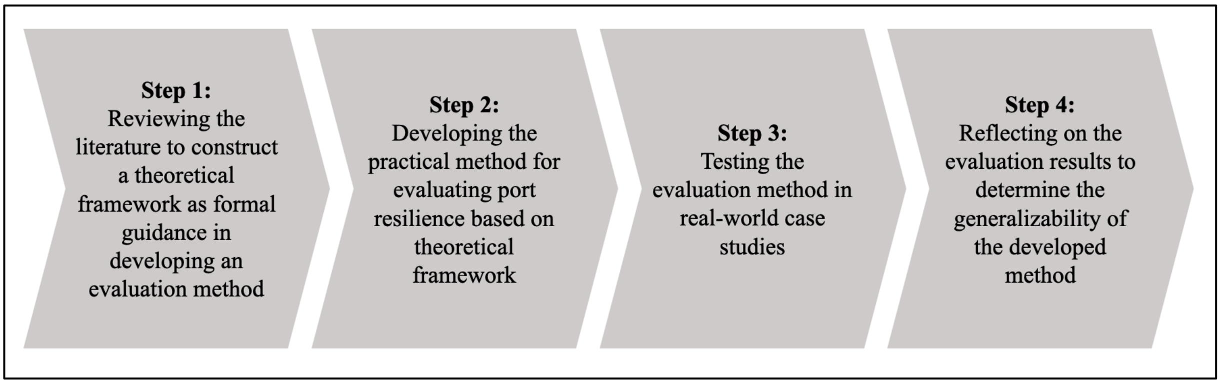

Figure 2. Formal guidance for developing port-resilience evaluation method (adapted from McMeekin et al., 2020)

1.3.3 Research design

A research design describes a strategy for answering the research questions. To determine the research design used, this study considered the philosophical foundation and the formal guidance used in developing the method. The philosophical foundation chosen in this study is pragmatism. In general, pragmatism is not committed to a single form or research method for gaining knowledge. Pragmatists believe that acquiring knowledge is a continuum rather than two opposing and mutually exclusive poles of either objectivity (positivist) or subjectivity (interpretivist). Regarding the mode of inquiry, pragmatism is situated somewhere between the paradigm continuum. Positivism typically relies on quantitative methods and inductive reasoning, whereas constructivism emphasizes qualitative approaches and deductive reasoning. However, pragmatism offers a flexible and more reflexive approach to research design.

Regarding the formal guidance used, as explained earlier, four steps were involved in developing the evaluation methods in the study. While the chosen philosophical foundation (pragmatism) offers flexibility in the choice of research design, it is important to consider that the multi-step nature of the formal guidance will have implications for the research design, which also consists of several different phases. To facilitate this, this study utilized a Multiphase Mixed-methods Case-Study (MM-CS) research design to address the research question.

Guetterman and Fetters (2018) define MM-CS as a research design that utilizes a *"mixed methods design and uses the case study as one of the research instruments*." MM-CS design can enhance the depth and breadth of data collection in developing and testing the evaluation method proposed in this study. To achieve this goal, qualitative and quantitative data collection methods are used, combined with case studies as the primary research instrument, to provide a comprehensive understanding while testing the method in the real world. This approach increases the validity of the findings, reduces the likelihood of bias, and can help uncover unexpected relationships, patterns, and interactions beyond the existing theoretical concept, contributing to novel theoretical and practical insights. Moreover, MM-CS research designs generate in-depth and broad insights by applying the method developed from a theoretical framework, enabling researchers to make more generalizable conclusions (Yin, 2013).

Thus, this research is divided into three parts, as shown in Figure 3. The first part of this study focuses on constructing a scientific yet practical method to evaluate port resilience in the archipelago. The first step was to conduct a structured literature review to clarify the concept of resilience and key terminology often used interchangeably with resilience. In addition, literature on island theory and the complexity of ports in island states was reviewed to inform the development of the evaluation method. The result of the literature review was a theoretical framework used as the scientific basis for developing the method. The second step in this part is to operationalize the theoretical framework into an applicable method using mixed methods, both quantitative and qualitative analysis. The final result of this step is a practical method for measuring port resilience based on a strong theoretical foundation.

The second part of this research involves the application of the developed method for guiding port resilience evaluation in archipelago ports through multiple case studies. This phase provides a practical demonstration of the method's applicability in different port contexts. The case studies were selected based on diverse port types in Indonesia that have suffered port shutdowns due to natural disasters in the past. The results from this phase could contribute to developing more effective strategies for improving resilience ports in similar contexts.

The final part of this research evaluates the generalizability of the method proposed in this study. The evaluation was conducted by reflecting on the data collection efforts and the implementation process of the three case studies. The results of this cross-case reflection can explain under what ideal conditions the method can be implemented and what must be done to achieve that ideal situation so that the method can be applied in other ports, whether similar to the context in the case studies or not.

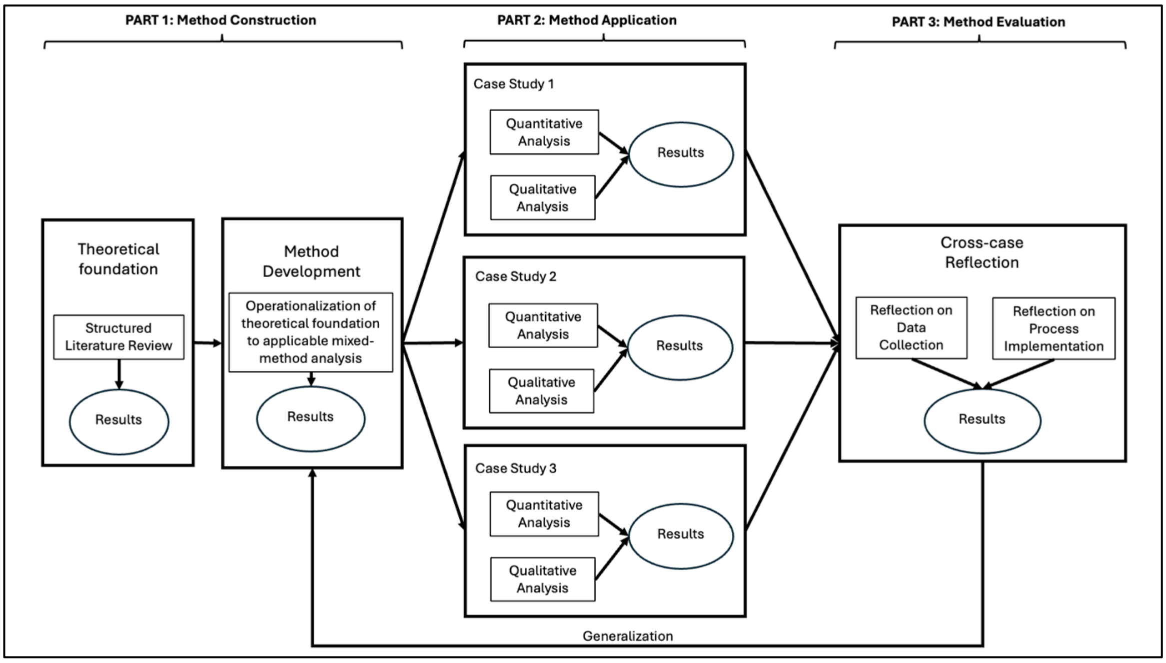

Figure 3. The multiphase mixed-methods case-study research design adopted in this study

1.3.4 Structure of the thesis

The structure of this thesis is based on a mixed methods case study (MM-CS) research approach used to develop practical methods for evaluating port resilience in an archipelago context. The thesis is organized into eight chapters and divided into three main parts based on the MM-CS research approach undertaken in this study. This chapter serves as an introduction to the research.

Part I consists of Chapters 2 and 3 and focuses on method development. **Chapter 2** is dedicated to a literature review on port resilience in general and the unique characteristics of ports in archipelagos. It provides an overview of the characteristics and complexity of island port operations. It reviews the concept of resilience, including key terminology related to resilience, to increase clarity before operationalizing in the context of island ports. **Chapter 3** focuses on operationalizing the theoretical framework into a method that can be implemented through a mixed (qualitative-quantitative) analysis in evaluating port resilience in island regions.

Part II comprises three chapters and focuses on applying the method for evaluating port resilience in an archipelago nation, with Indonesia being selected as the case study. **Chapters 4, 5, and 6** demonstrate how the method guides the resilience evaluation of ports in Indonesia. The three case studies chosen have unique characteristics that represent most of the population of ports in Indonesia.

Part III comprises Chapters 7 and 8, focusing on the method evaluation. **Chapter 7** evaluates the method through data collection and implementation process reflection. This chapter examines the lessons of applying three different case studies regarding the ideal data inputs required to implement the method and how difficult it is to execute each phase in the proposed method. The results of this reflection will provide insight into how far this method can be generalized to ports similar to the case studies and ports with different characteristics. **Chapter 8** explains the conclusions in answering the research questions, scientific and societal impacts, limitations of the study, and suggestions for future research.

2 Theoretical foundation

Several theoretical concepts underpin this research. This chapter reviews these theories, elaborating on their concept and application within the scope of research. Specifically, this chapter aims to (1) consolidate the theoretical definition of port resilience and its associated attributes to provide clarity before operationalizing it for addressing the research questions formulated in Chapter 1 and (2) establish a theoretically grounded perspective to characterize large-scale archipelagos and the complexity of port operations in the archipelago.

Chapter 2 consists of three sections. Section 2.1 reviews various definitions and theories on port resilience from the existing literature. Various interpretations of port resilience are identified in this section to obtain a more precise and consistent concept of resilience to answer the research questions in this study. Section 2.2 characterizes the concept of islands and archipelagos from the perspective of islands' relationality that forms a complex spatial network. Section 2.3 presents the complexity of port systems on large-scale islands as socio-technical systems and components of complex island spatial networks.

2.1 The resilience of port infrastructures

This section delves into the concept of resilience concerning port infrastructures. Resilience was initially defined by Holling (1973) in his study of ecological systems, describing it as a system's capacity to absorb and sustain changes in environmental conditions. Resilience research has been conducted extensively in many domains, such as psychology, business, ecology, socio-economics, organizational, and engineering systems (Hosseini & Barker, 2016). However, when it comes to the definition of resilience, including in the realm of port infrastructure and maritime transport, there is no consensus among researchers, given their diverse backgrounds, ideologies, viewpoints, and particular aspects of ports they focus on in their research (Grainger et al., 2018). Consequently, the port infrastructure resilience concept remains unclear and inconsistent (Omer et al., 2012). This sub-section seeks to clarify the concept of resilience in port infrastructure used in research based on a systematic literature review within the scope of port infrastructure and maritime transport studies.

2.1.1 Definition of port resilience

The first thing this study did was to try to consolidate the definitions of resilience that exist in the current literature. Consolidated definitions can help this study answer research questions by providing a precise and consistent conceptual reference. To keep the discussion focused, the definitions of resilience reviewed are those provided by researchers in port infrastructure and maritime transport. Scientific articles outside of these fields are beyond the scope of this study. Table 2 lists the definitions of port infrastructure and maritime transport in the existing literature in chronological order.

Table 2. Definition of resilience in port infrastructure and maritime transport literature

Author	Definition
Berle et al. (2011)	*"Resilience is the ability to handle a disruption without significant impact on the ability to serve the network mission."*
Woolley-Meza et al. (2011)	*"The ability to maintain its original structure and connectivity in the face of its components fail."*
Earnest et al. (2012)	*"Resilience is quickly returning to full capacity after losing port functionality."*
Omer et al. (2012)	*"Resilience is defined as the ability of the system to bounce back after disruptive events and return to its normal value delivery levels."*
Baroud et al. (2014)	*"Resilience is the time needed for a disrupted system to regain full operation after a disruptive event."*
Trepte and Rice Jr (2014)	*"Resilience is the ability to build the capacity to handle and withstand disruptions to continue to flow cargo through."*
Justice et al. (2016)	*"The ability to absorb a disruption while maintaining its function, form, and structure."*
Su et al. (2016)	*"The ability of the system to recover from negative impacts caused by hazards."*
2017 - Calatayud et al. (2017)	*"Resilience is the ability to cope with a disruptive event and thus enhanced network connectivity."*
Shaw et al. (2018)	*"Resilience is the capability to return to or bounce back to a normal state after a disturbance or crisis."*
Stergiopoulos et al. (2018)	*"Resilience is the ability to resist and withstand disturbances affecting performance."*
Alderson et al. (2019)	"*Resilience is the ability to withstand the changes in the properties and structure of the network following a disruptive event."*
Wu et al. (2019)	*"Resilience is the ability to recover its basic structure and connectivity from disaster."*
Asadabadi and Miller-Hooks (2020)	*"Resilience is the ability to withstand disruptions by maintaining expected network performance, such as total served demand in the network, total port throughput, and total shipping cost."*
Mou et al. (2020)	*"The resilience denotes the ability of the system to withstand damage and remain operational after disturbances, representing the invulnerability of the network and its ability to recover from harm."*
Verschuur et al. (2020)	*"Resilience is the ability to resist and recover from, and adapt to, adverse events."*
Dui et al. (2021)	*"Resilience is the ability to recover its performance after system components fail."*
Notteboom et al. (2021)	*"Resilience is the ability to adapt to an enduring situation or overcapacity and recover into normal demand patterns from external shocks."*
Wan and Tao (2021)	*"Resilience is the systems' ability to absorb and resist external shocks, and to take measures to respond actively and prompt the system to reach a new equilibrium state quickly."*
Dirzka and Acciaro (2022)	*"The ability to prevent the collapse of the infrastructure connectivity and to withstand even major catastrophic incidents."*

The arrangement of definitions in chronological order above shows that there is no indication of consistent use of the definition of resilience over a period of time. This shows that since the emergence of research on port resilience at the end of 2010, the definitions used have varied. The definitions used can be derived from differences in the references used or the development of definitions based on the school of thought of the researcher doing it.

Three perspectives were identified from the definitions above to consolidate the definitions used in this research. These perspectives are based on the similarity in meaning of the keywords used to represent the characteristics of a resilient port. The following are the three perspectives identified from the definitions above, which are why the definitions and interpretations of port resilience differ.

Perspective 1. Focus on withstanding disruptions

The first perspective to define the resilience of port infrastructures involves their capability to endure disturbances without straying significantly from predefined performance benchmarks. Holling (1973) introduced this perspective with the concept of ecological resilience, which focuses on a system's inherent capability to absorb and withstand changes. This ability is also mentioned as absorptive capability (Darayi et al., 2020), which other literature calls the "performance buffer," signifying the system's residual performance after being subjected to disruptions (Dui et al., 2021).

This capability underlines the degree to which a port can absorb the effects of disruptions while keeping their consequences at a minimum. This perspective implies that a system's state is not invariably stable and may unexpectedly transition to a worse condition in the face of escalating disturbances. The adoption of this perspective in defining port resilience perspective has been discussed and advanced in the work of multiple studies, including Alderson et al. (2019), Berle et al. (2011), and Trepte and Rice Jr. (2014). Their work reinforces this view of resilience as an intrinsic capacity of a system to withstand disruptions, thus maintaining its performance despite experiencing significant degradation.

Perspective 2. Focus on reacting to disruptions

The second perspective on defining port resilience focuses primarily on a port's ability to react swiftly and decisively after unexpected disruptions. It underscores the agility of port actors in marshaling necessary resources, fostering collaboration, and coordinating efforts to initiate recovery measures promptly following disruptive events. Other works of literature mentioned this ability as an *adaptive capability* (Hosseini et al., 2015; Hosseini & Barker, 2016). This perspective focuses on the ability of the system to respond quickly to the impact of disruption and reduce the latency in initiating recovery.

This perspective arises due to the reality that many real-world infrastructure systems consist of social and technical components. When infrastructure is affected by disruptions, a return to normal operations doesn't happen instantaneously. There is often a delay as stakeholders make decisions and orchestrate their responses (Shaw et al., 2018). During this time, port performance can remain in a disturbed condition without directly starting to return to its original state. This perspective underscores the active role of social or human decision-makers within the port management system who strive to maintain operations, albeit in a degraded form, during disruptive events and exert efforts to commence the recovery process as quickly as possible.

Some examples of response to disruptive events in port infrastructure include resource mobilization, collaboration initiation, and coordination to transition into a recovery-ready state post-disruptions (Python & Wakeman, 2016). Prakoso et al. (2018) and Gong and Liu (2020) reinforce the importance of this perspective on port resilience. They uphold that resilience is characterized by swift and effective responses, enabling a system to quickly pivot toward recovery in the aftermath of disruptions.

Perspective 3. Focus on time to recover

The third perspective defines port resilience based on its ability to quickly bounce back to its original state after a disruption, measuring it according to the system's performance levels. This perspective underscores the temporal aspect of resilience, suggesting that recovery timing is essential in assessing resilience. This perspective originates from the definitions provided by Pimm (1984) and Tilman and Downing (1994), who emphasize the stability of a system in proximity to its balanced, steady state. This viewpoint is also consistent with Holling's (1996) concept of "engineering resilience," which focuses on restoring system performance efficiently. Using this perspective, one could gauge the resilience of a port by its recovery time - the period required for the port to revert to its original state. This concept inherently suggests the assumption of a unique, stable condition that the system will invariably aim to return to after a disruption. Researchers such as Omer et al. (2012), Shaw et al. (2018), and Wu et al. (2019) have also incorporated this perspective in their definitions of resilience.

In this dissertation, we adapt the concept of resilience by synthesizing the three perspectives to enhance precision and consistency in its definition and to foster a comprehensive view of resilience. Each viewpoint provides a unique contribution to understanding port resilience. By incorporating all three, we cater to an extensive array of scenarios and conditions, enhancing the adaptability of the definition across various types of ports.

Moreover, combining these perspectives reflects the port operations' complexity and real-world relevance. Given that ports and disruptions can vary vastly in type, scale, and impact, reliance on a single perspective might fall short of capturing the multi-facet resilience of a port. Thus, in alignment with these three perspectives, we propose the following definition of resilience in the context of port infrastructure:

"Port resilience refers to the engineered ability of a port infrastructure to withstand disruption[1], promptly act in response, and quickly initiate and carry out recovery strategies to reinstate acceptable performance following a disruption."

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[1] Disruption refers to more severe events that have the potential to cause substantial or lasting operational disturbance to a port's operations, which adapted from Rousset and Ducruet (2019)

The literature review underscores the multifaceted nature of port resilience, revealing its potential to be defined from numerous angles. This dissertation focuses on resilience through the lens of three widely accepted perspectives within port infrastructure and maritime transport literature, as mentioned above. Drawing upon the definitions provided in the reviewed literature, this study defines a resilient port as one that is capable of (1) *withstanding*, (2) *promptly responding*, and (3) *quickly recovering* from disruptions.

2.1.2 Operationalization of port resilience

Wan et al. (2017) argue that it is not sufficient to understand the theoretical concept of resilience by only using its definition. Only relying on the definition when implementing the resilience concept will increase the ambiguity and the difficulty for decision-makers in applying resilience concepts effectively. This is because a holistic understanding of resilience involves contextual nuances, the dynamic nature of resilience, and its practical implications in real-world scenarios. To clarify the resilience concept derived from the three perspectives outlined in the definition used, this study can delineate the three capabilities[2] of resilient ports. Thus, a resilient port can be measured based on two main dimensions: system performance and time. The resilience curve is used as a primary tool to facilitate operationalizing this two-dimensional port resilience concept.

A resilience curve is a common approach to describe critical infrastructure resilience within a specific disruption scenario from the systems engineering perspective, as Wan et al. (2017) and Poulin and Kane (2021) mention. Bruneau et al. (2003) first introduced the resilience curve. The curve, later termed the "resilience triangle," is the initial conceptual model for describing a system's resilience. The resilience triangle summarizes rapid performance loss and a recovery trajectory of the system. Following the resilience triangle, a "resilience trapezoid" emerges as a generic view of resilience curves for real-world engineered systems and critical infrastructure (Henry & Ramirez-Marquez, 2012). Resilience trapezoid curves describe system behavior that may include phases of performance loss, pre-recovery degraded performance (i.e., response), and recovery phase trajectory. Figure 4 illustrates the resilience curve with the resilience trapezoid, in which the system's performance typically begins at a certain level, decreases due to a disruption, works at the level of residual performance, and finally recovers (ideally back to the original level). This study uses this curve as the main tool to operationalize the definition and port's resilience capability.

Let function $f(t)$ represents an indicator of port performance as a function of time t. Port infrastructure exists to provide service, and one can measure port performance using three categories of metrics: *port availability, productivity,* and *service quality* (Poulin & Kane, 2021). *Port availability* measures the functional capacity available of the port infrastructure. In its most straightforward implementation, this measure represents the "*number of functional components or capacity available that can be used to deliver services*" (e.g., crane availability at a seaport). *Port productivity* measures the actual quantity of service provided by a port infrastructure. In the port context, literature (Rousset, 2018; Touzinsky et al., 2018) often relates port productivity

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[2] In this study, to avoid confusion and align with existing literature, the terms “ability” and “capability” can be used interchangeably because they both refer to being able to do or achieve something

indicators as the number of ships berthed, the amount of cargo processed, or the number of passengers visited. Lastly, *service quality* measures the level at which services are delivered, and this measurement is typically assessed from the customer's perspective. An example of a service delivery level could be the time it takes for cargo to be unloaded from a ship and made available for pick-up or transport. This is often called "cargo dwell time" in the port industry. A shorter cargo dwell time indicates a higher service delivery level because cargo "dwells" or stays at the port for a short time.

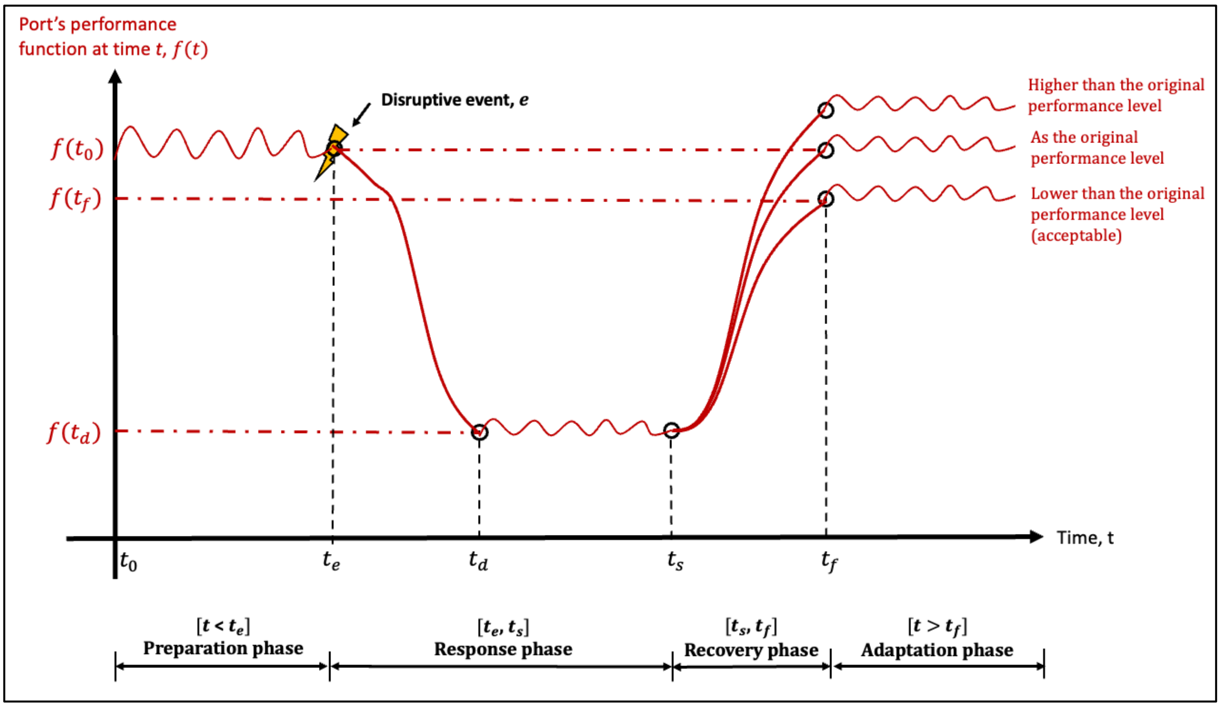

Figure 4. Resilience curve (trapezoid) that describes resilience as a system performance-time dependent function.

Based on the resilience curve (trapezoid) in Figure 4, ports undergo four distinctive phases related to a disruption. The first phase is the "***preparation phase***" that starts before the disruptive events e takes place at t_e $(t < t_e)$. In this phase, the port operates with a stable initial performance $f(t_0)$. In this preparation phase, the port management implements mitigation strategies to minimize the impact of disruptions. In addition, the preparation phase can also be used to prepare action plans or procedure needed to be taken in subsequent phases.

The second is the "***response phase***" that starts after the event e disrupts the port performance at the time t_e until it starts to recover at time t_s. During this phase, the stable initial performance $f(t_0)$ decreases until the residual performance $f(t_d)$ arrives on time t_d. The decrease of value $f(t)$ is presented in a non-linear form in alignment with the representation of real-world phenomena of port infrastructure and maritime network studies, as shown by Lhomme (2015), Wu et al. (2019), and Mou et al. (2020). From the time t_d, the resilient port retains the residual performance while the port's stakeholders also respond to the disaster's impact by accessing resources or collaborating to ensure the recovery can be initiated as quickly as possible at time t_s.

The third is the "***recovery phase***" that takes place from t_s to t_f. In this phase, the port restores the residual performance $f(t_d)$ to its original value $f(t_0)$ or to a minimum acceptable performance (which can be lower or higher than the original performance), $f(t_f)$, as demonstrated by the work of Touzinsky et al. (2018) and Rousset and Ducruet (2019). In the real world, stakeholders can interpret the sign that the port is back to normal differently. The standard of return to normal port performance needs to be reconfirmed with stakeholders, considering that the point of return to performance will be used to describe a resilience cycle.

The fourth is the "***adaptation phase***", which represents the time after the port performance is officially stated to be fully recovered ($t > t_f$). In this adaptation phase, a port can learn from past events to enhance its preparedness, response, and recovery efforts for future disruptive events, aiming to improve its overall resilience. In this study, the *adaptation phase* can be interpreted as a *preparation phase* for the port stakeholders to prepare for future disasters. Although the *adaptation* and *preparation phases* are theoretically distinguished, this study interprets the adaptation phase as preparation for the next operational threat.

This study recognizes these phases as the "resilience cycle," a term adopted from Breuer et al. (2021). These phases (preparation, response, recovery, and adaptation) reflect the iterative and continuous process of enhancing a port's resilience over time (UNCTAD, 2022). The key connection between these phases is that the preparation phase can be used as an opportunity not only to minimize the impact of the disaster but also what actions will be taken in the response and recovery phases. Actions taken in the response and recovery phase can be spontaneous or have been through previous planning in the preparation phase. All actions in these two phases are then monitored or reviewed to see if there is a need for improvements to the port infrastructure or to improve certain procedures. Improvements and adjustments are then made in the adaptation phase, which can also be interpreted as a preparation phase to prepare for the next disaster. The cycle then continues. Based on the division of distinctive phases of the resilience phase and adopting the concept of the resilience cycle, we can thus operationalize the resilience definition more accurately and consistently.

Figure 4 illustrates how the resilience curve is used to operationalize the three capabilities in this study's definition of a resilient port. The first capability is withstanding disruption, often associated and used interchangeably with absorptive capacity in literature. (Hossain et al., 2019). This capability represents how the port maintains performance at a certain point after a disruption. Performance-level measurement is commonly used as a main metric to evaluate the capability of a port to withstand disruption. The metrics mainly consider the disruption's size or scale, including its severity, extent, or impact. Specifically, this metric is used to evaluate port residual performance and disruptions' depth of impact. The residual performance metrics describe the remaining performance level following the disruptive event.

In the figure, residual performance is indicated by $f(t_d)$. A typical attribute used for evaluating this residual performance of a port is ***robustness*** (Hosseini & Barker, 2016; Kim et al., 2021), often defined as to what extent the port's performance remains intact after being affected by disruptions. In addition, depth of impact is the complement of residual performance to measure the ability of a port to withstand disruption, which can be measured by how much the port performance decreased from $f(t_0)$ to $f(t_d)$. This is associated with ***vulnerability*** as another important attribute of port resilience (González Laxe et al., 2012; Lhomme, 2015; Nursey-Bray et al., 2013). A deeper decrease in the port service level $f(t_0)$ to $f(t_d)$ represents a higher vulnerability of the port when faced with certain types of disruptive events.

The second capability is responding immediately to disruptive events, often associated or used interchangeably with adaptive capacity (Gharehgozli et al., 2017; Hosseini & Barker, 2016) in literature. This capability represents how the port actors gather resources or devise strategies for starting port recovery after the disruption. The response can differ according to how much the disruption affects the port. In other words, the ability of a port to withstand disruption influences how port actors can or should respond to the disruption. Time-duration measurements are usually used as the main metrics to evaluate response-ability (Poulin & Kane, 2021). An example is the duration between $[t_e, t_s]$ or $[t_d, t_s]$ (Galbusera et al., 2018). A shorter duration for the time interval $[t_e, t_s]$ and $[t_d, t_s]$ indicates that the port is highly responsive to disruptions, where the time spent to react, gather resources, and devise strategies is short, showing that the port is responsive to disruption. While this duration is generally underexplored in the literature on port or maritime resilience, it is often attributed to ***responsiveness***, which describes the duration spent in the disrupted state before starting port recovery (Zhang et al., 2019).

The third capability is quickly recovering from disruption, often associated and used interchangeably with restorative capacity. This capability represents the ability of a port to bounce back to the minimum acceptable performance, which can be below, similar to, or above the original performance (Poulin and Kane, 2021). The literature commonly uses two types of measurement to evaluate the ability to restore. The first measurement is time-duration based, quantifying the time spent on the performance restoration trajectory during the recovery phase $[t_s, t_f]$.

Rapidity is often used to attribute this duration, describing how quickly the port's performance level can be restored from the degraded performance $f(t_d)$ to an acceptable required level $f(t_f)$ (Cho & Park, 2017; Mou et al., 2020). The second way to evaluate the capability is by combining performance-level and time-duration-based measurements, which evaluate port performance changes over time. These measurements are calculated using the curve's derivative to determine how system performance changes over time in the recovery phase. The ***recoverability*** attribute is often used to operationalize this measure, following Rabadi et al. (2013), which calculates the speed of port recovery measured immediately after the recovery process begins. This calculation was expressed as a derivative, $\frac{df(t_d)}{dx}$. Figure 5 depicts the resilience curve and includes all labels or attributes that represent the capabilities of the port resilience based on the definition used in this study. This conceptualization is essential to make port resilience operationalization and evaluation more consistent.

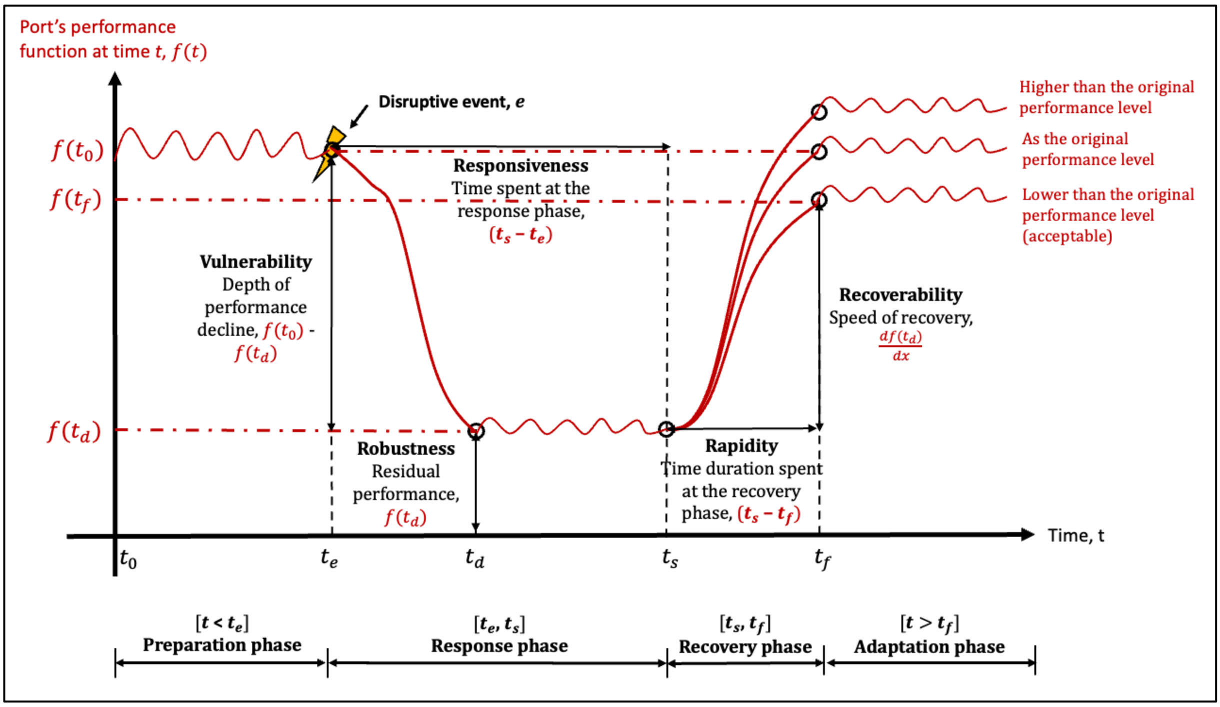

Figure 5. Operationalization of attributes that represent resilience capabilities using the resilience curve

In summary, the theoretical review in this sub-section focuses on consolidating the definition of resilience as applied to ports and maritime transport. The theoretical review found three main perspectives from researchers in defining port resilience. In this study, the definition of resilience is an amalgamation of these three perspectives. Thus, resilience is an engineered ability comprising three capabilities: withstand, respond to, and recover from disruptions. This study uses the resilience curve to clarify the three capabilities. It identifies the various attributes used to operationalize the three capabilities so that the measurement and evaluation of port resilience can be more precise and consistent.

2.1.3 Conditional resilience: the effect of interventions in port resilience

The emerging concept of resilience in the context of port infrastructure brings an essential question. Can resilience be conditioned so that ports have a stronger level of resilience? If possible, what types of decisions can enhance the resilience of port infrastructure? From an engineered system resilience standpoint, the answer is yes. Resilience can be actively enhanced through deliberate design and decision-making, a concept known as *conditional resilience* (MCEER, 2005). *Conditional resilience* is rooted in recognizing that building port resilience is not just a passive characteristic but an active, ongoing process that demands continuous investment and effort. Conditional resilience involves conscious decision-making and shaping port infrastructures to enhance resilience by boosting specific capabilities[3].

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[3] The capabilities are in accordance with the definition of resilience used in this study, namely: withstand, respond to, and recover from disruptions.

McDaniels et al. (2008) demonstrate how conscious decision-making can enhance system resilience. They use '*ex-ante mitigation*' to refer to decisions before disruptive events. In contrast, *'ex-post adaptation*' refers to decisions made after such events, considering the extent of the disruptions' impact on the ports. This approach can strengthen resilience through risk mitigation actions taken before a disaster and responsive actions taken post-event. Figure 6 illustrates how conditional resilience is realized by consciously implementing decisions that enhance the resilience attributes of the port infrastructure.

In the figure, two arrows show how the two types of decision-making enhance the port's resilience. The first arrow shows how *ex-ante mitigation decisions* enhance resilience by minimizing the impact of disruptions so that the residual performance of the port can be higher than the condition without intervention. In other words, this ex-ante mitigation strengthens resilience by increasing port resilience. The second arrow shows how the effects of ex-post adaptation can shorten the time needed to restore port performance to its original state. Ex-post adaptation strengthens resilience by increasing the port's responsiveness and speed in recovery efforts. Implementing both is expected to minimize the extent of the curve, indicating that port resilience is improving.

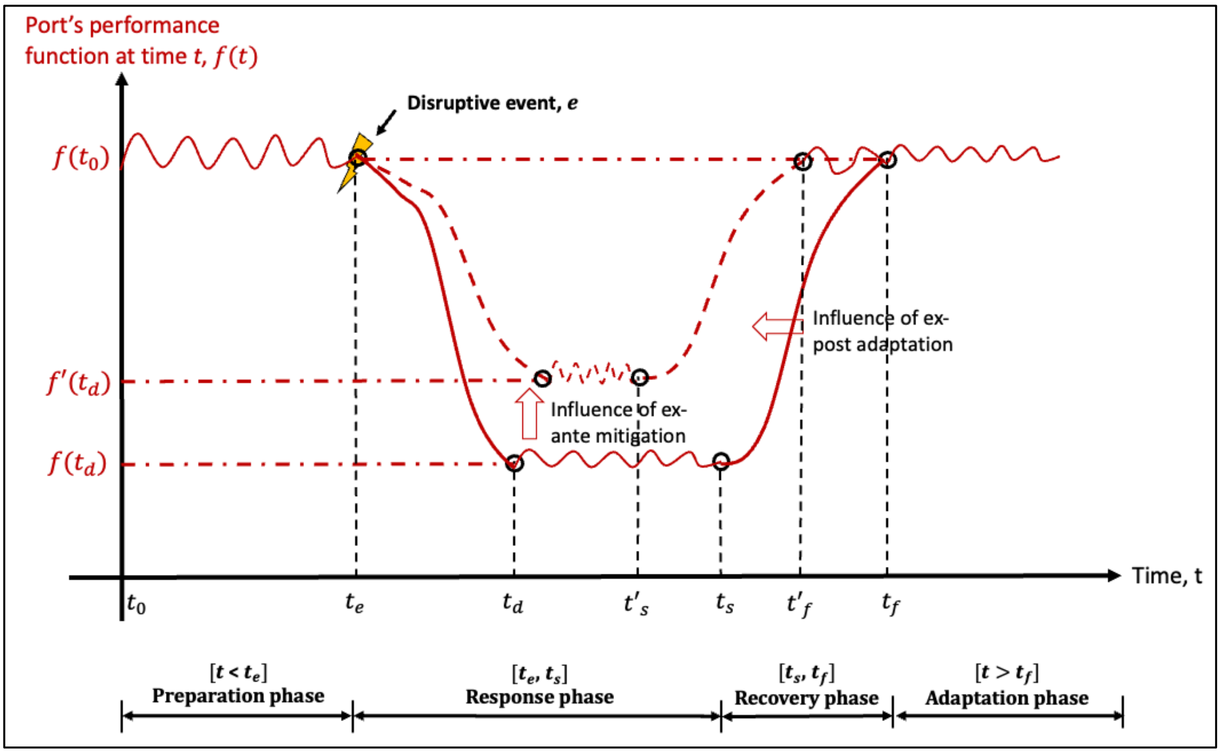

Figure 6. Illustration of the concept of conditional resilience using the resilience curve diagram

The operational forms of ex-ante mitigation and ex-post adaptation can theoretically be categorized into two based on their focus, namely whether they focus on physical infrastructure or processes that support port operations (UNCTAD, 2022). According to UNCTAD (2022), existing port infrastructure resilience interventions can be divided into four main categories: (i) infrastructure preparedness and (ii) process preparedness under the ex-ante mitigation category, and (iii) infrastructure adaptation and (iv) process adaptation under the ex-post adaptation category. The category of infrastructure and process preparedness is carried out before a disaster occurs, generally in the preparation or adaptation phases[4]. Infrastructure and adaptation processes are carried out after a disaster, which can be done in the response and recovery phases. A brief explanation for each intervention from the review of existing resilience literature is as follows.

Infrastructure preparedness ensures a port's physical structures and equipment are strong enough to withstand and react to potential disruptions. The main objective of such preparedness is to limit the impact of disruptions (such as natural disasters) on physical assets and maintain the highest possible residual performance. In other words, infrastructure preparedness focuses on increasing port robustness. The literature highlights various strategies to operationalize infrastructure preparedness, which include (but are not limited to):

- **Hardening**, an intervention scheme aimed at enhancing the structural integrity of port infrastructure. This refers to the initiative to make port facilities and equipment more resilient to damage or malfunction. It could involve reinforcing infrastructure, fortifying buildings and structures, or upgrading to sturdier equipment (Omer et al., 2012). For example, the Port of New York secured $59 million for longer-term mitigation efforts to harden the physical infrastructure to minimize the impact of future hurricanes by building barriers, stockpiling sandbags, and moving equipment to higher ground (Smythe, 2013).
- **Redundancy** involves creating duplicates of essential infrastructures to provide backup or alternative solutions during disruptions. For example, investing in multiple gantry cranes might be prudent to provide redundant capacities (Chen et al., 2017). If a disaster were to occur, causing one of the cranes to collapse or become damaged, the additional cranes would serve as backups. This approach ensures the continuity of operations and safeguards against potential productivity losses. It allows for the rapid restoration of normal functions after a disaster, minimizing downtime and mitigating the broader impacts on port operations and related supply chains.
- **Modularity** refers to a scheme where physical infrastructure is constructed so that its various components can be readily separated and reassembled (Donnan et al., 2020). The strength of the modular design of physical infrastructure lies in its inherent flexibility, allowing for easy separation and reassembly of different components. This modularity design proves invaluable when disruptive events occur. Often, these disruptions only impact specific parts of the physical assets, and a modular design allows for the prompt isolation of these damaged sections. The unaffected components can continue functioning, ensuring ongoing operations to the greatest extent possible. Furthermore, the damaged parts can be repaired or replaced without causing extensive downtime, enabling the port to absorb the disruption and recover more quickly. The investment in modular container cranes illustrates an example of this intervention (Notteboom et al., 2021). These cranes are designed with interchangeable parts, making

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[4] The adaptation phase in this study can also be considered as a preparation phase to prepare the port for future disruptions after evaluating the resilience cycle of previous incidents.

replacing or upgrading individual sections possible rather than replacing the entire crane when damage occurs. This improves the port's capacity to withstand disruptions by ensuring continuity of operation, thereby significantly enhancing overall resilience.

- **Capacity tolerance** involves designing physical infrastructure to continue functioning, albeit at a reduced capacity level during disruptions. The idea is that, in the event of a disruption, a system or component can still operate at a lower capacity until the issue is resolved (Omer et al., 2012). For instance, creating extra berth length beyond the existing demand embodies this concept. It enables the port to sustain operations even if a portion of the berths becomes temporarily unavailable. Capacity tolerance essentially prepares for unexpected surges in demand, e.g., caused by a disruption in another part of the port system due to an external event. For example, if a port's regular container demand requires a crane capacity of a specific number of TEUs per hour, the port might invest in a crane with a higher capacity. This way, the port can accommodate sudden peaks in demand, ensuring smooth operations and minimizing potential bottlenecks or disruptions (Jones et al., 2011). This preparedness for sudden changes reinforces the port's resilience and operational robustness.

Process preparedness is the set of measures taken related to port managerial capabilities and collaborative efforts with stakeholders, such as carriers, government, or international agencies, to enhance resilience before disruptive events. Most of the intervention schemes carried out in process preparedness are to prepare action plans or procedures involving multi-port actors regarding what needs to be done to reduce the impact of disasters and accelerate infrastructure repairs, especially to deal with the risk of prioritized disruptions based on historical data observations. The schemes identified in the literature include (but are not limited to) the following:

- **Personnel training** refers to providing specialized training and development opportunities to the personnel involved in port operations. The primary aim is to improve port personnel's knowledge, skills, and capabilities to respond to disruptive events (Kim et al., 2021). Examples of personnel training are establishing clear communication channels, implementing comprehensive emergency response plans, and ensuring that personnel are regularly trained on safety procedures and best practices (León-Mateos et al., 2021). Cross-training personnel also can be conducted to ensure that critical port functions can be performed even if key staff members are unavailable.
- **Response planning** involves developing an organized, structured protocol for dealing with disruptive events. Such a plan enhances a port's ability to react swiftly by laying out specific emergency procedures. These steps provide a clear blueprint for action during disruptive events, aiming to decrease the disruption's impact on port operations and enable a proficient reaction (Becker et al., 2012). For example, the Port of Houston has created a comprehensive hurricane disaster manual (UNCTAD, 2022). This provides meticulous instructions on the gradual securing and shutdown of terminal facilities in the event of a hurricane, thereby ensuring the safety of the infrastructure and facilitating a prompt recovery after the storm has passed.

- **Coordination** signifies uniting various stakeholders and resources to achieve a mutual goal. It involves orchestrating the resilience efforts of port operators, government agencies, emergency responders, and other parties before an event to prevent conflicts when deploying resilience strategies. Grouping port stakeholders according to their responsibilities can bolster the efficiency of information sharing and data relevant to their roles (Shaw et al., 2018). This enables each stakeholder to have access to necessary information, allowing them to make informed decisions and take suitable actions that will enhance the port's ability to withstand disruptions and react promptly. A practical example of this intervention is the resilience toolkit for climate change provided by the US National Oceanic and Atmospheric Administration (NOAA, 2023). This toolkit offers guidelines for port operators and government agencies to collaborate effectively when responding to natural disasters.
- **Cooperation** signifies the act of various stakeholders working collectively towards shared objectives. This involves fostering stakeholder partnerships and relationships to pool knowledge and resources (Li et al., 2022). One example of such collaboration is Public-Private Partnerships (PPPs). In this context, public port operators could collaborate with private terminals to exchange knowledge and resources. For instance, a public port operator might form a strategic alliance with private terminals to devise a joint response plan in anticipation of significant disruptions to port operations (Python & Wakeman, 2016).

Infrastructure adaptation is a post-event intervention focused on the required physical assets necessary to continue operations in disrupted states and to bring the assets to pre-existing conditions or recover to an acceptable level. More specific to the port context, infrastructure adaptation refers to the capacity of a port to adapt and modify its physical assets to cope with the impacts of disruptive events. Several strategies identified in literature that concern infrastructure adaptation include (but are not limited to):

- **Repurposing** involves altering the functionality of existing or outdated infrastructure to accommodate new uses or to adapt to changing circumstances resulting from disruptive events, as indicated by Dandekar (2013) and Finucane & Tarnowy (2019). By repurposing existing infrastructure, ports can increase their adaptability to deal with rapidly changing situations at a minimal cost. A prime example of this strategy is seen at Port Said, which reopened an older section of the Suez Canal to alleviate congestion during the Ever Given blockage. This allowed traffic to flow while rescue operations were underway, demonstrating an effective, cost-efficient response to a significant disruption (Labrut, 2021; UNCTAD, 2022).
- **Relocation** is a post-disruption scheme that emphasizes shifting services, equipment, or essential physical assets to alternate locations within the port or elsewhere to maintain operations after suffering disruptions (Merk, 2018). Stakeholders typically resort to this scheme when a port or terminal has sustained such extensive damage that repairing or rebuilding is not economically viable or the existing site is evaluated as at high risk of natural disaster occurrence. In such cases, shutting down the compromised facilities and

relocating operations to another site becomes a viable alternative. The new site selection should consider locations less susceptible to disruptions and offer economic advantages.

- **Reparation** involves repairing physical assets that have suffered damage or functional deterioration. The primary goal of reparation is to promptly restore a structure or system to its pre-disruption condition after encountering disruptions. A notable instance of this strategy in action was the aftermath of Hurricane Matthew in 2016 in the Port of Freeport, Bahamas. Following the typhoon, the Freeport terminal halted operations to repair cranes, and container vessels were forced to reroute vessels to other ports during the repair period (AON Benfield, 2017).
- **Reconstruction** refers to the complete rebuilding or renovation of port physical assets, often after large-scale impacts of disruptive events. Reconstruction is often aimed at improving or modernizing the ports into a state that is better than the previous state. One example of reconstruction is the Port of Meulaboh in Indonesia after the tsunami of 2004. The reconstruction took up to 12 months, including constructing a new T-shaped wharf with deepened water depth at low tide, completed one year after the event (UNDP, 2005).

Process adaptation is a post-event intervention that focuses on the required managerial and human resources to restore the port to pre-existing conditions or bring the port to a better condition. Several schemes identified in the literature concern process adaptation, including (but not limited to):

- **Operational flexibility** denotes a port's capacity to quickly and efficiently adjust its normal operations in response to disruptions and environmental changes. For instance, the Ports of Los Angeles in the United States demonstrated this by extending operating hours to sustain their cargo handling capacity amid disruptions caused by the COVID-19 pandemic (Brunton, 2021). Operational flexibility can also be seen in having a versatile workforce capable of taking on tasks outside their usual responsibilities when key personnel are unavailable (Kim et al., 2021).
- **Organizational agility** represents a post-event scheme emphasizing efficient internal and external communication, collaboration, and coordination with other stakeholders to deal with extraordinary situations. This strategy aids in garnering the resources necessary for executing initiatives in response to disruptive situations, such as materials, finances, and specialized knowledge. Moreover, organizational agility ensures that all relevant stakeholders are informed and actively involved in the recovery process, and it facilitates prompt, efficient decision-making with less stakeholder conflict. A good example can be found in the Port of Ho Chi Minh. In response to the surge in demand during the COVID-19 pandemic, an initiative to increase the container handling capacity was executed quickly. This proactive planning led to an 8.5% increase in Vietnam's container volume in 2020 (Speedmark, 2021).

Based on real-world implementation examples, as shown by the example above and Shaw et al. (2019), ex-ante mitigation and ex-post adaptation have an interconnection. First, how well the ex-ante mitigation decision maintains residual performance will influence how much spontaneous (unplanned) ex-post adaptation will be taken during both the response and recovery phases. A spontaneous ex-post adaptation scheme that will be taken certainly needs to be based on the results of the assessment of the level of impact that disruption has on the port. Second, the purpose of ex-ante mitigation itself can be developed where the goal is not only to increase the residual performance of the port (robustness) but also to prepare a plan for how the port responds to damage and repairs infrastructure damage experienced, regardless of what the impact of the damage is. In resilience planning, this is often called contingency planning or planned ex-post adaptation.

Thus, the resilience intervention paradigm is perpendicular to the three capabilities described in the definition of resilience used in this study. This review of theoretical relationships is important given that evaluating resilience in ports is not enough to know what the resilience curve looks like but why it looks the way it does. By understanding that resilience interventions are perpendicular to the three capabilities of resilience, lessons learned can be more careful, where port performance in the *response, recovery, and adaptation phases* may be strongly influenced by decisions made in the *preparation phase.* This can be a valuable lesson for every port that wants to improve its resilience in the future.

2.2 Characteristics of large-scale archipelagos

Archipelagos, as defined by Stratford et al. (2011), are geographically dispersed groups of islands. The term "archipelago" stems from the Greek words "arkhi," meaning principal, and "pelagos," meaning sea or ocean. Generally, this term applies to any collection of islands, regardless of their size, number, or location. The distinguishing feature of an archipelago is its geographical division of islands by bodies of water. Such division often culminates in unique cultures, languages, and lifestyles on each island due to geographical isolation.

Grydehøj and Hayward (2014) argue against conflating archipelagos with groups of isolated or solitary islands. Solitary islands, entirely encircled by water, are relatively simple to define. However, scholarly literature suggests a more comprehensive understanding of an archipelago. Pugh (2016, 2018) argues that an archipelago embodies an interconnected network of islands, with each island exhibiting distinct island-related traits commonly known as the 'island effect'. Unique to archipelagos is a phenomenon known as island relationality - the interconnectedness and interdependencies among islands - which leads to a diverse range of characteristics (Chandler & Pugh, 2018; Grydehøj & Casagrande, 2020). This network of islands relationality underscores the reciprocal influence and dependencies among islands within an archipelago, thereby constructing a relational space that challenges conventional island boundaries. This perspective emphasizes the interactions and relationships between islands, including trade links, environmental dependencies, and cultural exchanges. It acknowledges that changes on one island can have far-reaching impacts on others within the same archipelago (Chandler & Pugh, 2018).

While islands display a wide range of sizes and characteristics, mainstream island studies typically categorize islands within archipelagos into two primary groups to depict the general aspect of island relationality (Hong, 2017, 2018). The core-periphery economic model (Krugman, 1992) is adopted for this categorization. The first category is the main island, often called the mainland. In literature, the mainland is depicted as the primary region within the archipelago, continuously developing into its economic and political centers. This island usually hosts the largest population, the most advanced infrastructure, and the highest levels of economic activity. Often serving as a transport hub, the mainland provides frequent and large-capacity transportation services for passengers and cargo.

Given its central role and economic significance, the mainland is generally more accessible, featuring direct connections to other major islands, cities, or countries. Luzon in the Philippines Archipelago exemplifies this category (Rutland & Walter, 1974). The second category is the peripheral islands. These islands are considered less developed and more impoverished compared to the mainland. Peripheral islands usually possess a certain level of economic development or industrialization, but their influence is not as substantial as that of the mainland. In some cases, these islands are predominantly rural areas with less economic development, smaller populations, and restricted resource access due to underdeveloped infrastructure. Okinawa Island in Japan (Kerr, 2011) and Belitung Island in Indonesia (Purnaweni et al., 2019) are examples of peripheral islands.

Within island studies, scholars and transport geographers are paying increasing attention to the theoretical relationships within archipelagos. Two predominant perspectives on island relationality have emerged. The mainstream perspective adopts a mainland-island framework for understanding these relationships (Grydehøj & Casagrande, 2020). One such illustration is found in the Croatian archipelago, where smaller or medium-sized islands near the Adriatic Sea mainland coast experience varying degrees of mainland influence (Starc, 2020). An alternative perspective invites researchers to consider the connections between the islands themselves. Pugh (2016), followed by Grydehøj and Casagrande (2020), advocates for a "thinking with the archipelago" approach, encouraging an examination of the interactions between islands, the sea, and the vessels that connect them. Agius et al. (2022) illustrate this idea through the island-island relationships in the central Mediterranean archipelagos, which effectively responded to the COVID-19 pandemic and economic recovery by declaring "COVID-19 free" tourism zones. They propose the island-island relationality as a complement to the conventional mainland-island model. It is particularly suitable for analyzing the complexity of small-scale archipelagos.

The literature often presents the dichotomy between the mainland-island and island-island relational perspective as a standard paradigm for describing archipelagos' complexity (Favole & Giordana, 2018; Grydehøj, 2015; Hayward, 2012; Hong, 2017; Swaminathan, 2014). This dichotomy tends to overgeneralize, perpetuating the notion that large-scale archipelagos constitute a separate category in the academic discourse. Large-scale archipelagos, comprised of multiple main islands and numerous peripheral islands, form multifaceted relational networks. For instance, Destyanto et al. (2020) revealed strong container trade interdependence between main islands, such as Java and Sulawesi, in the Indonesian archipelago, which each connects with many peripheral islands. Similarly, Go (2021) highlighted the high interdependence of trade patterns among the Philippines' main islands, such as Luzon and Mindanao, which maintain connections with peripheral islands. Tsiotas (2015) observed high connectivity between the main islands in Greece that maintain links with numerous small peripheral islands.

This study recognizes the complexity of island spatial relationships and their relational positions, thus viewing large-scale archipelagos as a multifaceted network that embodies the two theoretical types of island relationality. Therefore, a large-scale archipelago is considered as a space where the mainland-island and island-island relationality types coexist and interact, creating a complex spatial network. Complex spatial networks can be analyzed to understand how different elements within the spatial network are structured and how they interact and evolve. The concept of complex spatial networks can be effectively applied to the study of archipelagos (Destyanto et al., 2021; Gascuel et al., 2016) or to a group of interconnected islands to understand their relational dynamics.

Ports are essential for connecting islands and enabling islands' relationality, as Destyanto et al. (2021) demonstrated. By adopting concepts from graph theory (Diestel, 2017), each port located on an island can be seen as a vertex in the network. The connections between islands' port in the archipelago, like maritime trade routes and passenger transportation links, serve as the edges of this network. The most typical and straightforward representation of this multifaceted network is the multiple-hub-and-spoke model, commonly seen in empirical studies of island relationality within large-scale archipelagos (Destyanto et al., 2020, 2021; Tsiotas & Polyzos, 2015). In this model, the ports in the central mainland (usually the location of the capital city) serve as both a national and an international hub. As a national hub, this main port connects to other main islands, further serving as a domestic hub. Connections extend to ports in peripheral islands from these domestic hubs, forming relationships with other peripheral islands. As an international hub, this port biasanya memiliki skala luas yang besar dan kedalaman kolam pelabuhan yang tinggi to connect with international shipping lines consisting of transcontinental liner services.

Figure 7 (a) illustrates a simplified version of relationality among the islands in the Indonesian archipelago. One of the significant factors contributing to shaping this relational pattern is the presence of port connectivity among the islands (red, brown, and blue dots represent ports). This island relationality can be described as a complex spatial network in Figure 7 (b). In Figure 7 (b), A represents the central mainland, B represents the main islands, and C means peripheral islands. Note that multiple ports are identified per island. Blue dots are foreign ports, red are main hub ports, and brown are regional ports. The bi-directional arrows acknowledge the ubiquitous connection between islands, symbolizing cargo trade and passenger flow. This complex model of island relationality can be observed in empirical research such as studies of Indonesian (Destyanto et al., 2020), Greek (Tsiotas & Polyzos, 2015), Philippine (Go, 2021), and Finnish (Makkonen et al., 2013) archipelagos. Employing this perspective allows us to view the islands within a large-scale archipelago not as isolated entities but as integral components of a unified archipelagic system with complex interdependencies.

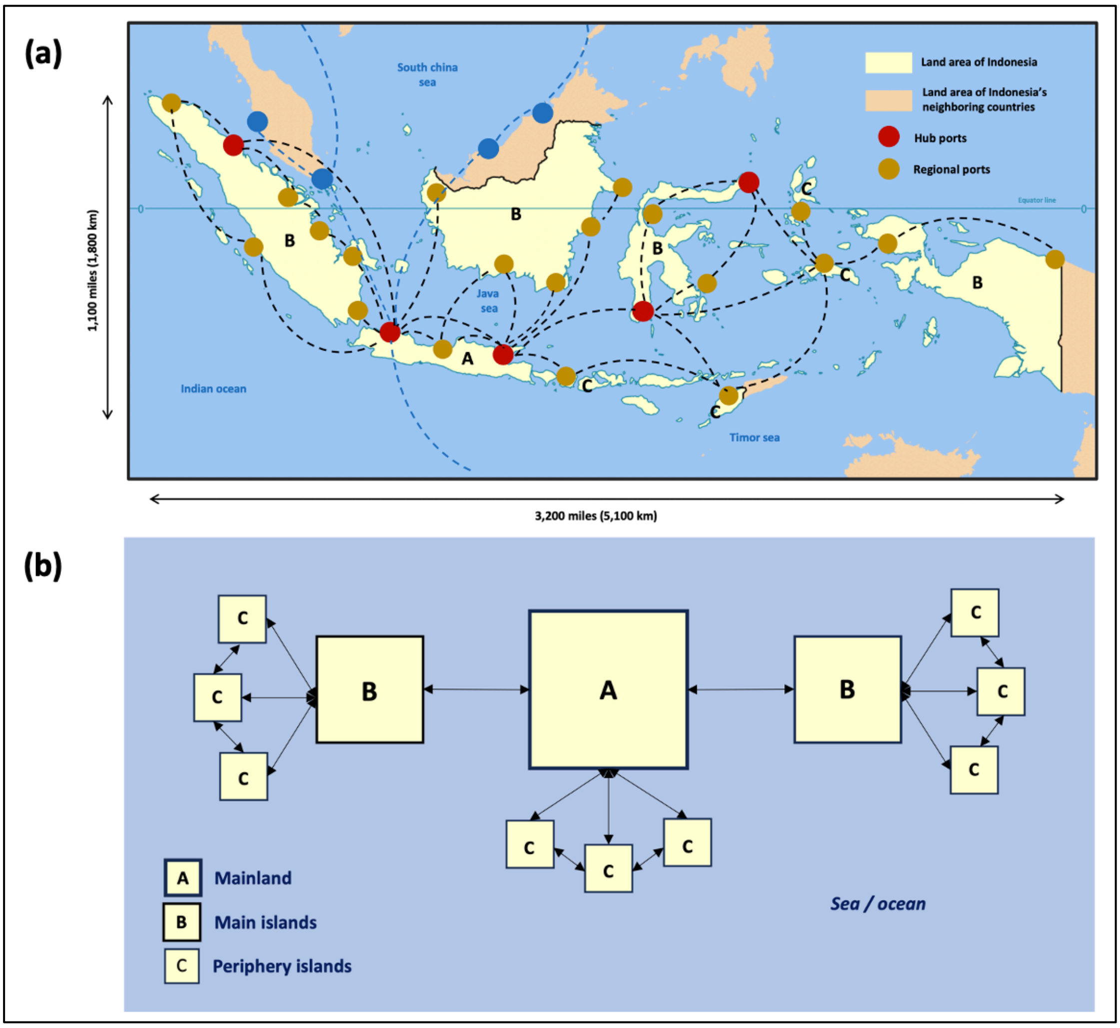

Figure 7. (a) The simplified version of islands' relationality enabled by the presence of ports in the Indonesian archipelago and (b) a schematic complex spatial network of islands in a large-scale archipelago

2.3 The complexity of port operations in large-scale archipelagos

There are several interpretations of what constitutes a port. Stopford (2009), for instance, offers a definition often found in literature, characterizing a port as a geographical location where ships can dock to unload and load cargo, typically in a sheltered, deep-water area such as a bay or river mouth. Notteboom et al. (2022) offer a broader definition, seeing a port as a pivotal logistic junction within global supply chains characterized by a strong maritime character. It serves as a functional and spatial collection of activities directly or indirectly associated with transportation, transformation, and informational procedures within these global supply chains. Both definitions highlight the integral role of ports as essential links within transport networks, serving as transit points or gateways for cargo moving to and from the sea. They emphasize a port's role as a point of exchange between maritime and inland transport systems and as a convergence point for varying modes of transport.

In the context of archipelagos, ports serve a multifaceted role that extends beyond cargo handling; they are also instrumental in passenger transportation. As outlined in Indonesian Government Regulation No. 69 of 2001 (BPK, 2023), a port is a distinct area composed of land and adjacent waters designated for government activities and economic operations. It acts as a docking station where vessels can anchor, facilitating the boarding and disembarking of passengers and loading and unloading cargo. Equipped with maritime safety facilities and additional port activities, it is a transitional hub for intra- and intermodal transportation. In large-scale archipelagos, ports are indispensable for connectivity and economic development. Sandee (2016) delineates three crucial reasons underscoring this importance. First, ports enable the transition of cargo and passengers across different transportation modes, serving as a vital junction between sea and land. Second, ports also serve as gateways for international and domestic travelers, accommodating ferry services, cruise ships, and other passenger vessels. This functionality is vital for tourism, significantly contributing to local and national economies and fostering cultural exchange. Third, within vast archipelagos, ports provide temporary storage for goods, a necessity given that large vessels often cannot access remote island ports due to infrastructural limitations. This temporary storage buffer allows goods to stay close to the remote islands, potentially reducing the logistics cost needed to deliver goods from the mainland to the periphery islands.

Managing ports within archipelagos entails distinct challenges arising from the diverse port types linked to the unique spatial characteristics of each island (Agius et al., 2021; Tovar et al., 2015). The term "spatial" herein refers to the specific geographical attributes of an individual island, including population size, level of industrial development, types of terrain, and prevailing climate, among others (Grydehøj & Hayward, 2014). These factors significantly contribute to the heterogeneity observed in port development across large-scale archipelagos, leading to significant variation in assets, roles, functions, and institutional organization. Ports in such archipelagos can vary widely, ranging from minor docking areas to expansive centers encompassing multiple terminals and industrial clusters. These ports' organizational structure and ownership may span a broad spectrum, ranging from private, joint-venture, or public-private partnership to pure public governance ownership (Amin et al., 2021; Nyman et al., 2020).

Yudhistira and Sofiyandi (2018) and Castanho et al. (2020) suggest conceptualizing ports within archipelagos or islands as complex entities. This suggestion stems from the observation that the economic structure in an "island economy" diverges substantially from conventional economic frameworks, thereby leading to a striking diversity in island ports. Nevertheless, it is imperative to acknowledge that the interpretation of "complexity" is not uniform but depends on the chosen perspective. In this study, the complexity of port operations within a large-scale archipelago is viewed through two complementary theoretical lenses: firstly, it examines ports as socio-technical systems, and secondly, it considers them as components of complex spatial networks. The subsequent sub-section will explain the rationale behind adopting this dual-perspective approach.

2.3.1 Port operations as socio-technical systems

In large-scale archipelagos, the effectiveness and efficiency of port operations depend on how well various components work together. To identify the components that contribute to the port operations, we adopt the concept of system hierarchy and emergent behavior as outlined in the primary text of Systems Engineering in conceptualizing a complex system (INCOSE, 2023). A system is a structured assembly of interrelated parts or elements. Each element, viewed as a discrete[5] component of a system, is designed to meet specific requirements (INCOSE, 2023). The interaction among these elements can give rise to certain collective behaviors known as 'emergence.' Rousseau et al. (2018) describe emergence as a system's unique attributes that its elements do not have. Adopting the concept of system hierarchy and emergent behavior allows us to break down complex systems like ports into smaller interacting components to understand how each part's characteristics and interactions influence the behavior of the overall system (Guerra, 2017).

In examining how these technical and social components are interconnected in more detail within the port context, we have drawn insights from O'Hara et al. (1999) and Hutchings (2019). The work underscores that the analysis of technical aspects of socio-technical systems should encompass both the technology and the tasks designed to achieve organizational objectives. In addition, when analyzing the social aspects, it is important to consider the managerial structure and the roles of that structure. The following is how social and technical components in the ports are interconnected, building upon the work of O'Hara et al. (1999) and Hutchings (2019).

In the case of generic cargo ports, the technical aspect can be categorized into two types based on the critical tasks in port operations: the first task centers on cargo handling within the port area. In contrast, the second involves technology supporting the flow of goods or cargo beyond the port area. Berths, quay cranes, and/or gantry cranes (Sachish, 1996; Sunitiyoso et al., 2022) belong to the former category, while ships and inland trucks belong to the latter.

The social aspect of ports consists of the structure and roles of the port actors. Various actors and stakeholders have jurisdiction over specific functions in the port and the potential to determine port productivity (Slack & Frémont, 2005). The first layer of social actors directly involved in port planning and operations are port or terminal operators, port authorities, and government and regulatory agencies. The second layer of actors handles passenger and cargo operations. These actors include shipping companies, ship operators, and inland transport carriers. While the first layer of actors provides the port handling capacities in the logistics chain or passenger transportation, the second layer controls the volume of freight or passenger flows that are critical in determining the productivity and safety of port operations (Fabiano et al., 2010).

To accomplish successful port operations, the port actors must work together in a coordinated manner. Shipping lines and port authorities coordinate to reserve berths and communicate vessel movements within the port. Terminal operators interact with shipping lines to load and unload cargo safely and efficiently. Along with terminal operators, inland carriers collect and convey cargo from and to its inland destinations. The interaction between social and technical aspects in the ports is conceptualized in Figure 8. This research investigates the complexity of ports in the archipelago, which aligns with the systems and complexity concept in systems engineering (INCOSE, 2023). Using the socio-technical system, we adopt a primary perspective to approach port complexity. By adopting the socio-technical system, we

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[5] In ISO/IEC/IEEE 15288, a "discrete component" refers to a distinct element of a system. These discrete components are designed to fulfill specific requirements within the overall system. In other words, "discrete components" are distinct pieces or modules of the larger system, each serving a particular function or purpose.

acknowledge that successful port operations depend on optimizing the interaction of both human (social) and technological (technical) elements (Meadows, 2008; Seiffert & Loch, 2005).

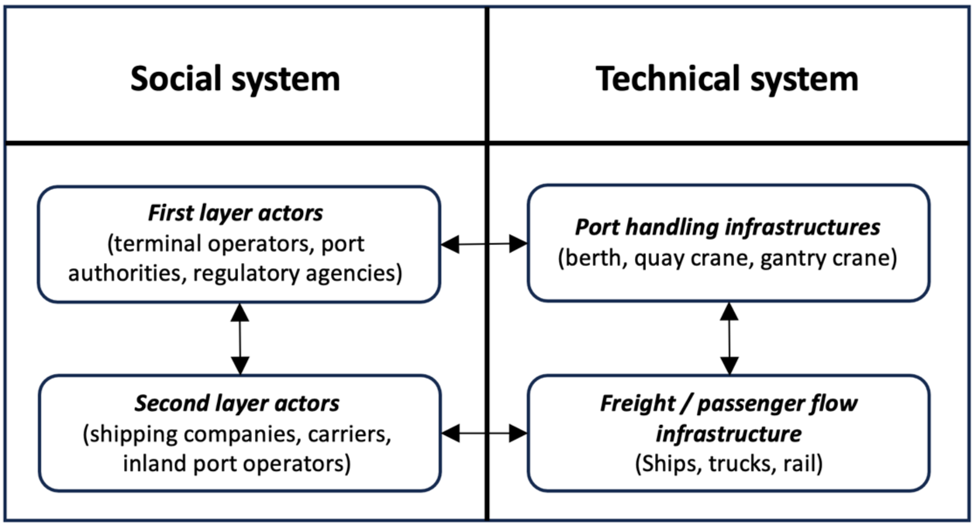


Figure 8. The schematic diagram of the interconnected technical and social components of port operations as a socio-technical system.

2.3.2 Port infrastructure as a component of complex spatial network

Ports as complex entities rely on the perspective that ports serve as an interface between two circulation systems - the maritime shipping network and the port's hinterland. Verschuur et al. (2022) stressed this perspective for analyzing the complexity of the ports since changing these two circulation systems can also affect port operations and development. This concept aligns with Gautz's *"theory of seaport location"* formulated in the early 1940s, which asserted that a port's function and evolution are significantly impacted by its geographical position (Yang, 1997), such as the degree of accessibility to the hinterland's economy and its connectivity to the maritime shipping network. These factors give specific ports a locational advantage or disadvantage over others, as Mou et al. (2021) also mentioned.

Regarding the influence of the hinterland on port development, Patton (1958) and Mueller et al. (2020) determined that the hinterland has a pivotal role in shaping the formation, evolution, and enhancement of port operations. The size of the market area or hinterland plays a role in determining the size of ports in a particular location (Ducruet, 2022). Port specializations also often align with their corresponding hinterlands. Port specialization, such as container, liquid bulk, dry bulk, break-bulk, or passenger ports, typically mirrors the hinterland's direct traffic or economy (Rodrigue & Notteboom, 2010). Moreover, recent empirical research validates that enhancing hinterland connectivity can boost port performance and stimulate growth. A study conducted by Wan and Luan (2022) shows that upgrading hinterland transport infrastructure can augment the productivity of ports such as Ningbo-Zhoushan, Nanjing, and Suzhou, thereby intensifying competition for Shanghai’s foreign trade container business. Shi and Li (2016) and Berg and De Langen (2011) underscored the significant positive impact of proactive involvement by the port authority in improving hinterland transport infrastructure to the port operations.

The interplay between ports and maritime networks and port connectivity studies has gained significant attention recently (Ducruet, 2020, 2022). The foundation of these studies is Robinson's (2002) assertion that a port's position within value-driven chain systems affects its operations. A prevalent proposition is that a port with high centrality in a regional maritime network will improve port operations and capacity growth. Ducruet and Itoh (2022) supported this hypothesis when they discovered that ports with numerous routes or high connectivity are more likely to expand their terminals and invest in advanced port facilities to mitigate congestion. This viewpoint contrasts with Heaver and Struder's (1972) hypothesis that increasing port connectivity would result in declining port efficiency. Wang et al. (2019) found that a port with direct shipping service connections to strategic hub ports will significantly influence trade and the transport of high-value cargo or strategic supplies within its region. This influence becomes particularly evident when the strategic hub port faces disruptions or severe congestion. Further, Ducruet (2013) demonstrated that the sea distance between two connected ports could influence the port's decision to specialize or diversify its operations. Therefore, changing the configuration of maritime networks can significantly impact port development and operations.

In this research, in addition to examining the complexity of a port through the socio-technical system lens, a seaport in large-scale archipelagos is viewed as an integral component of a complex spatial network inherent to its role as the enabler of island relationality. This perspective allows us to consider not only the internal components of a port and its operations but also the impact of the location of ports. Specifically, a port is part of an intricate spatial network interwoven with intra-island hinterland transport networks and inter-island maritime transport networks. Given the varying degrees of connectivity among these spatial networks, local changes—within maritime shipping, at the port level, or within the hinterland network—can trigger a chain reaction of potential effects across other network components (Buldyrev et al., 2010).

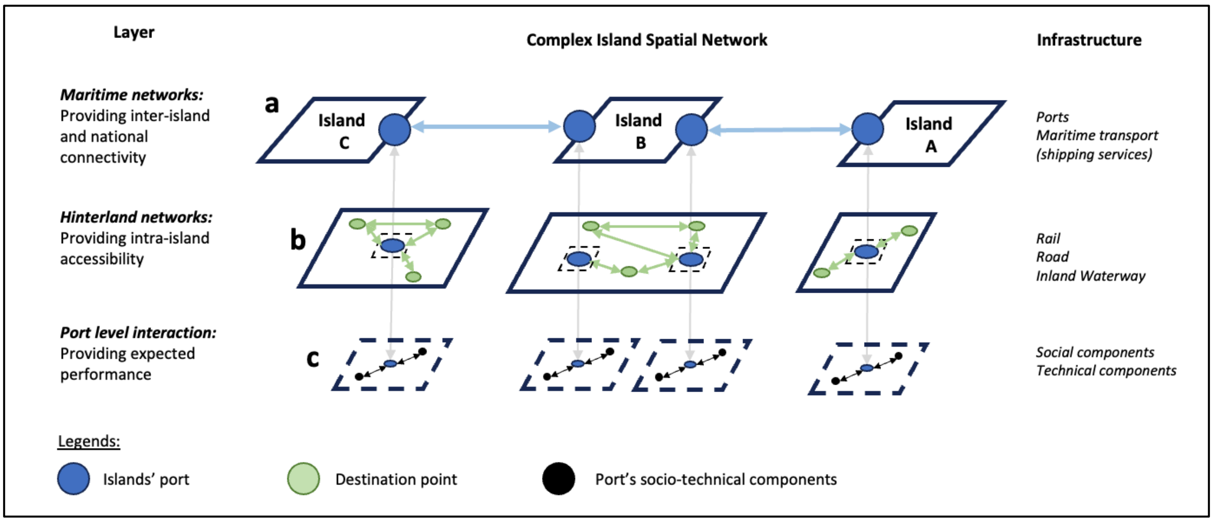


Figure 9. Schematic diagram of ports as components of a complex spatial network of islands

To conceptualize ports within the framework of spatial networks in archipelagos, this thesis positions a port within a multi-layered network. The spatial extent and economic linkages determine this network, which encompasses various interacting sub-networks, as Figure 9 illustrates. This network construction considers the concept of island relationality in the archipelago to incorporate the islands' unique influences on port operations. The topmost layer (Figure 9a) represents the maritime transport network, which can be simplified as the shipping services available (edges) connecting ports (vertices). Subsequently, the intra-island hinterland transport network (Figure 9b) captures the typical transportation systems (road, rail, and inland water transport) that facilitate the movement of commodities and passengers from the port to their respective destinations, and vice versa, at a regional scale. The base layer (Figure 9c) illustrates port-level interactions, encompassing various socio-technical components of ports that interact to achieve the expected performance in port operations.

Evaluating the behavior of port operations in light of the interplay between ports and their spatial location can yield a deeper understanding of their potential performance under varied conditions. A port disruption can cause large-scale ripple effects, affecting the connectivity of shipping services and the maritime spatial network (Verschuur, 2022). In addition, changing hinterland accessibility to ports can bolster or impede operations under different circumstances. The approach of viewing ports as part of a complex spatial network is rarely used in studies of archipelago ports, even though it’s more common for analyzing ports in global trade networks (Earnest et al., 2012; Ducruet, 2016). This thesis advocates for this perspective, as it recognizes the broad diversity of ports within archipelagos. The unique spatial traits of the islands influence their development, setting apart archipelagic ports from those in non-archipelagic settings. We argue that this theoretical perspective is important to enhance our understanding and analysis of port operations within an archipelagic context.

2.4 A Theoretical Framework for evaluating port resilience in the archipelago

This section maps the interrelationships between the theories and their influence in evaluating port resilience in the archipelago to organize the above theoretical foundations and make them more structured. In this study, the “XLRM” diagram is used to map the interrelationships between the theoretical foundations and how they influence evaluating port resilience in the archipelago. XLRM stands for four main components in describing framing decisions in the system and policy analysis exercises (Lempert, 2003; 2019). These components include the performance criteria of decision-makers (M), the alternative actions available to achieve those criteria (L), the uncertainties that can impact the relationship between actions and consequences (X), and the interconnections between actions, uncertainties, and performance criteria (R). Based on the literature review of the theoretical foundation, Figure 10 shows the theoretical foundation used in this study to evaluate port resilience in the archipelago.

The diagram recognizes natural disasters as external uncertainties (X). In this research, the type of disruption that is the focus is natural disasters because the potential for occurrence is very large in island countries (Djalante & Garschagen, 2017; Izaguirre et al., 2020; Lam & Lassa, 2017). The most obvious impact of natural disasters is the direct impact on the socio-technical components of the port, as well as the indirect impact on island connectivity (island relationalities), which will also affect how port operations run. These linkages are represented as system relationships (R) in this framework.

The devastating effects of natural disasters on ports and islands are illustrated below. The port infrastructure's condition directly affects the islands' shipping connectivity. If the port sustains damage and requires closure, shipping services must adjust their operations by skipping the port, canceling voyages, or detouring to other ports on the island. In the absence of alternative ports on an island, the closure of the sole port significantly reduces the island's connectivity and isolates it completely. Furthermore, natural disasters can also affect the hinterland network of the islands, thereby impacting port operations and recovery efforts. For example, landslides can obstruct road access, preventing trucks, personnel, and operators from reaching the port to carry out their tasks. As a result, port operations can also suffer from restricted hinterland access caused by natural disasters.

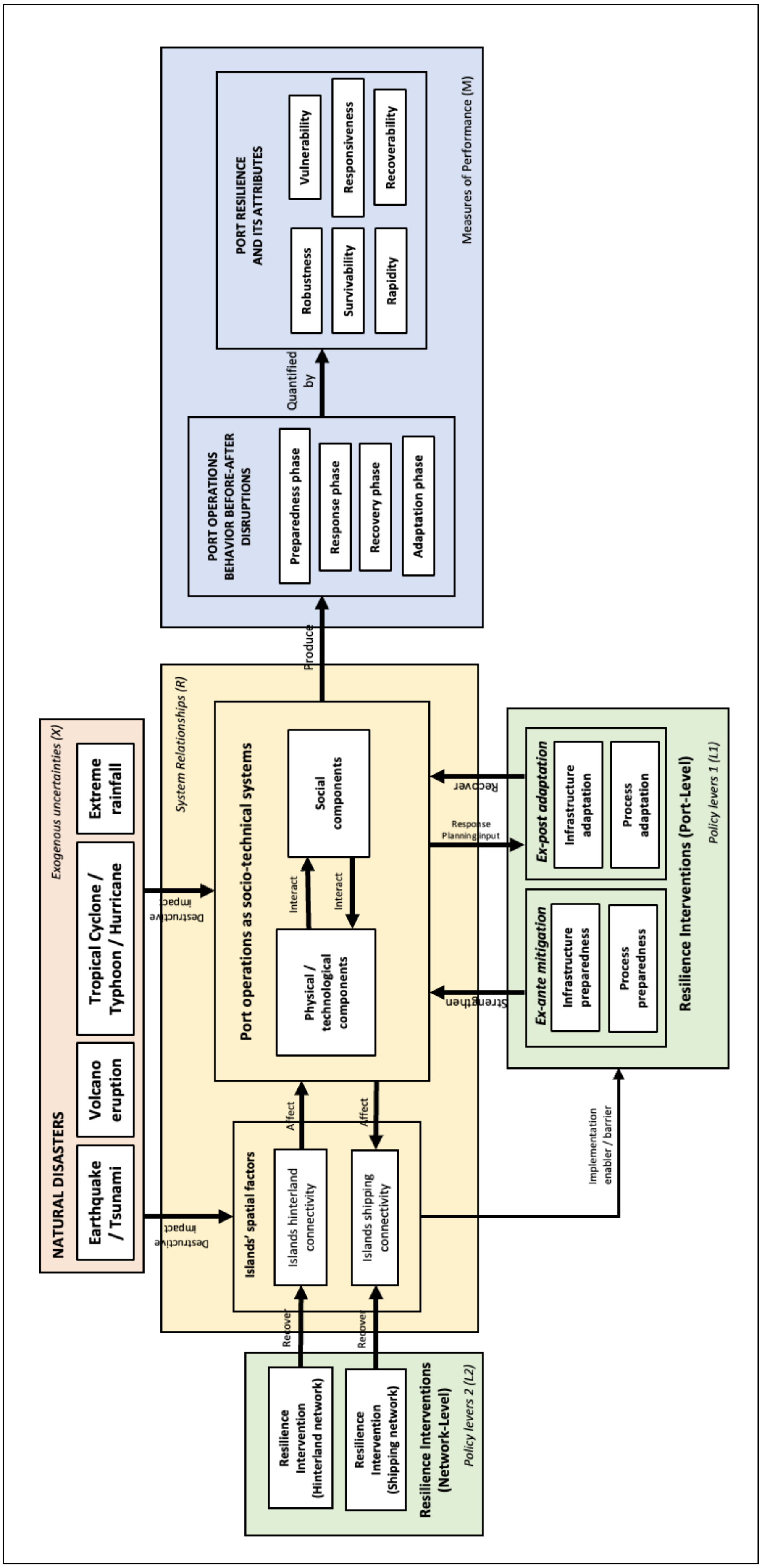


Figure 10. The theoretical framework use in this study used for evaluating port resilience in the archipelago

The islands' spatial factors also play a crucial role in enabling or impeding resilience interventions at the port level. What is meant by islands’ spatial factors are factors that affect an island's geographical isolation level in an archipelago and how dependent the island is on ports. The configuration of this network indirectly affects the implementation of ex-ante mitigation (pre-disaster) strategies and ex-post adaptation (post-disaster) strategies. These port resilience strategies are called policy levers 1 (L1) within the framework, represented as a green block. Moreover, network-level interventions (policy levers two or L2) are considered to facilitate the recovery of the hinterland and island shipping connectivity, which, in turn, impacts the implementation of resilience interventions at the port level. A one-way arrow from the L2 policy levers to the port system in the framework indicates that the analysis focuses on ex-post adaptation strategies. The main reason is that first-layer actors have limited influence on determining the ex-ante strategies for network-level interventions. By including the islands' spatial factors as critical variables within the System Relationships box, the theoretical framework recognizes that the factors specific to each island's location, directly and indirectly, influence the resilience of a port. This recognition distinguishes our analysis from other research on ports in non-archipelagic regions.

The interactions between exogenous uncertainties (X), policy levers (L), and system relationships (R) generate the behavior of port operations, which can be measured with selected port performance indicators throughout the resilience cycle's four phases: preparedness, response, recovery, and adaptation. The behavior of selected port indicator performance over time throughout the four phases will be used to quantify theoretical resilience attributes, such as robustness, vulnerability, survivability, responsiveness, rapidity, and recoverability. This study classifies these behaviors and attributes as measures of resilience performance (M). The theoretical framework presented in this section results from an iterative process, incorporating feedback from online sessions with experts and their validation of the framework. This theoretical framework will be used as a scientific basis for developing evaluation methods for port resilience in the archipelago.

3 A method for evaluating port resilience in the archipelago

Chapter 3 aims to develop a practical and scientific method for evaluating port resilience in large-scale archipelagos based on the theoretical framework established in the previous chapter. This chapter consists of six main sections. Section 3.1 outlines the design objectives and formal guidance for developing the method. Section 3.2 presents a detailed design of the empirical evaluation method to evaluate port resilience in archipelagos. Section 3.3 elaborates on the case study selection strategy and briefly describes the three case studies used to pilot the resilience evaluation method. Section 3.4 elaborates on how we evaluate this study's proposed port resilience evaluation method based on its pilot usage within case studies. Lastly, Section 3.5 provides concluding remarks from what is explained in Chapter 3.

3.1 Design requirements for a port resilience evaluation method in the archipelago

The primary objective of this chapter is to introduce a scientifically rigorous yet practical method to empirically evaluate port resilience in archipelagos. According to McMeekin et al. (2020), it is important to identify the specific design requirements for the empirical evaluation method. These requirements serve as guidelines for formulating and implementing the method. The following design requirements for the evaluation of port resilience have been defined, building upon the theoretical foundation and framework discussed in Chapter 2:

1. The method design must consider the complexity of port operations as a socio-technical system. This perspective emphasizes that the port's social and technical components are equally important in supporting port performance as expected.

2. The port resilience evaluation method must consider the large-scale archipelago as a complex spatial network, considering the "islands' spatial factors." These factors refer to the geographical positioning of the islands and their interconnectedness to other islands within the archipelago.

3. The port resilience evaluation method must consider port operations in large-scale archipelagos as socio-technical systems. It should account for the relevant social and technical components and their interrelationships, which contribute to the complexity of port operations.

4. Contextually, the port resilience evaluation method is aimed specifically at evaluating port resilience in large-scale archipelagos. It must represent the port as an integral part of a complex spatial network of islands, which includes crucial linkages between the port infrastructure, the maritime shipping network, and the hinterland network of specific islands.

5. The port resilience evaluation method should encompass short-term and long-term port performance behavior over time to ensure the incorporation of the dynamic development of port performance after disruptions and throughout the resilience cycle. To achieve this, the method should consider the phases of preparedness, response, recovery, and adaptation as components for the evaluation.

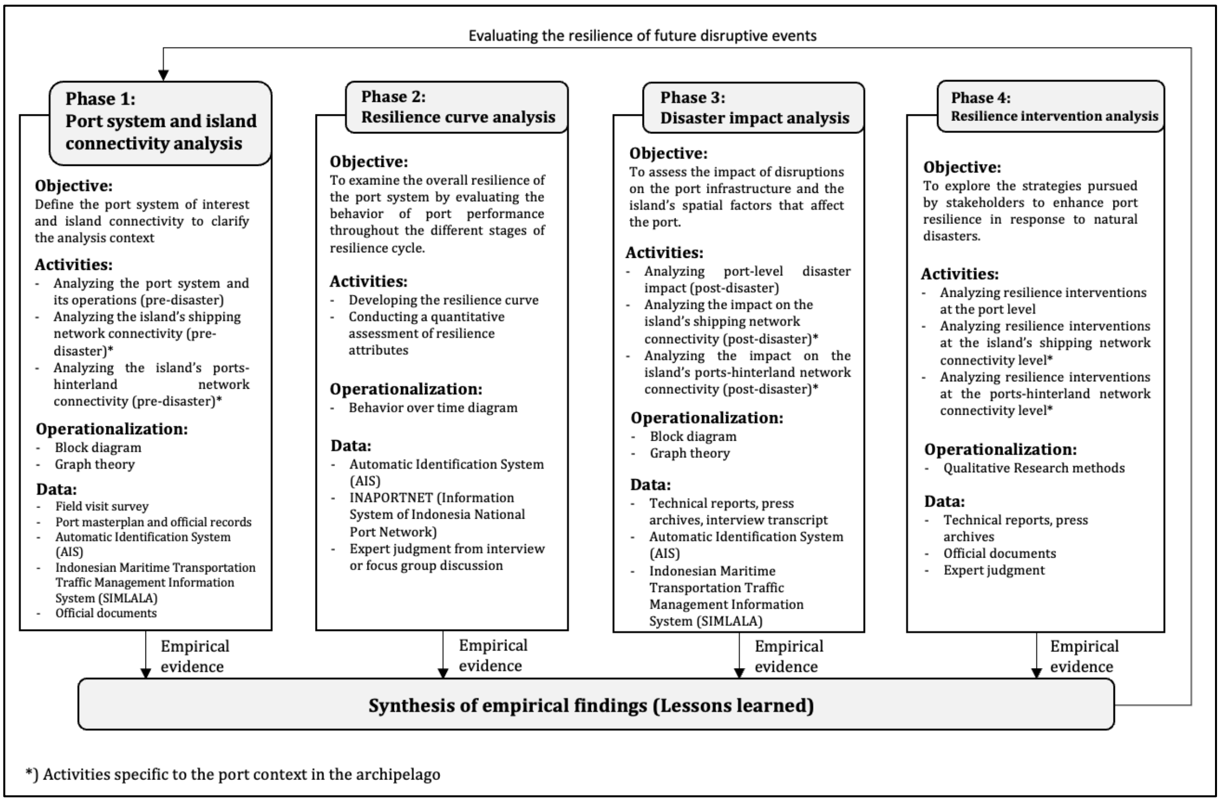
6. The port resilience evaluation method should enable the empirical evaluation of applied or attempted interventions in all four phases of the resilience cycle. This evaluation should provide valuable feedback for future efforts to improve port resilience.

7. The port resilience evaluation method should be adaptable for implementation in different types of ports within an archipelago and capable of addressing various types of natural disasters.

By considering the seven design requirements above, this research aims to ensure that the developed method can be relevant to the context of ports in island countries. These seven requirements follow the theoretical framework developed in the previous chapter.

3.2 An empirical evaluation method for port resilience in the archipelago

The method developed in this study follows the formal guidelines and theoretical foundation developed in the previous chapter. Based on the theoretical framework, the method introduces four analysis phases to evaluate port resilience in island regions comprehensively. The four phases are (1) port system and inter-island connectivity analysis; (2) resilience curve analysis; (3) disaster impact analysis; and (4) resilience intervention analysis, which includes objectives, activities, methods/tools, and data in each phase of the method as depicted in Figure 11.



Phase 1: Port system and island connectivity analysis

Objective:
Define the port system of interest and island connectivity to clarify the analysis context

Activities:
- Analyzing the port system and its operations (pre-disaster)
- Analyzing the island's shipping network connectivity (pre-disaster)*
- Analyzing the island's ports-hinterland network connectivity (pre-disaster)*

Operationalization:
- Block diagram
- Graph theory

Data:
- Field visit survey
- Port masterplan and official records
- Automatic Identification System (AIS)
- Indonesian Maritime Transportation Traffic Management Information System (SIMLALA)
- Official documents

Phase 2: Resilience curve analysis

Objective:
To examine the overall resilience of the port system by evaluating the behavior of port performance throughout the different stages of resilience cycle.

Activities:
- Developing the resilience curve
- Conducting a quantitative assessment of resilience attributes

Operationalization:
- Behavior over time diagram

Data:
- Automatic Identification System (AIS)
- INAPORTNET (Information System of Indonesia National Port Network)
- Expert judgment from interview or focus group discussion

Phase 3: Disaster impact analysis

Objective:
To assess the impact of disruptions on the port infrastructure and the island's spatial factors that affect the port.

Activities:
- Analyzing port-level disaster impact (post-disaster)
- Analyzing the impact on the island's shipping network connectivity (post-disaster)*
- Analyzing the impact on the island's ports-hinterland network connectivity (post-disaster)*

Operationalization:
- Block diagram
- Graph theory

Data:
- Technical reports, press archives, interview transcript
- Automatic Identification System (AIS)
- Indonesian Maritime Transportation Traffic Management Information System (SIMLALA)

Phase 4: Resilience intervention analysis

Objective:
To explore the strategies pursued by stakeholders to enhance port resilience in response to natural disasters.

Activities:
- Analyzing resilience interventions at the port level
- Analyzing resilience interventions at the island's shipping network connectivity level*
- Analyzing resilience interventions at the ports-hinterland network connectivity level*

Operationalization:
- Qualitative Research methods

Data:
- Technical reports, press archives
- Official documents
- Expert judgment

*) Activities specific to the port context in the archipelago

Figure 11. Overview of the method for evaluating port resilience in the archipelago

It is important to note that the phases in the proposed method are not *sequential*. This means that these phases do not have to be carried out sequentially, but one can be taken according to the objective or goal to be achieved. In addition, because the theoretical framework used consists of port resilience theory in general and also the characteristics of ports on islands, there are activities in these four phases that can apply to ports in general, and there are phase activities that need to be carried out in ports in the island context. Activities specific to island ports are marked with an asterisk (*), while others can be used for general non-archipelago ports. The following is a more detailed explanation of each phase.

3.2.1 Phase 1: port system and island connectivity analysis

The objective of this phase is to clarify the context of the analysis. By analyzing the system precisely and clearly, we can explain why specific interventions work, and others do not, often due to contextual factors. This phase entails analyzing the port system as the object of interest. The analysis activities in this phase zoom in on the theoretical foundation's System Relationships (R) blocks before disaster. In this phase, three activities are conducted: (1) Analyzing the port system and its operations; (2) Analyzing the island's ports-hinterland network connectivity*; and (3) Analyzing the island's shipping network connectivity*[6]. Each of these activities will be explained as follows.

Analyzing the port system and its operations

The analysis in this subsection begins by briefly introducing the port under study before starting the port operations analysis in more detail. This brief introduction begins by providing a brief profile of the port, such as the area, location, area plan, and role, as well as identifying the facilities and actors involved in the port. After providing an overview, port systems will be analyzed in more detail. The port system analysis focuses on the social and technical components, the functionality of these components, and the relationships between the components that contribute to port operations. To represent the principal components and functions of the port, a block diagram is customized as the primary tool for operationalizing this activity. The diagram consists of blocks representing the components and lines that connect the blocks to depict their relationships (SEVOCAB, 2023). Using this block diagram, one can highlight two key aspects of the analyzed port: critical port operations and the components that enable those operations. This study defines an *"operation"* as the operational task performed by a port, which can be conceptualized using a function-flow format (Stone & Wood, 1999).

Figure 12 illustrates the block diagram customized for the analysis to conceptualize the port as a socio-technical system. In the figure, we divide the block diagram into three sections: (a) port operations, (b) port technical components, and (c) port social components, which are then connected with one- or two-way arrows to show their relationship with each other. This customized block diagram generally explains the port operations process at the port of interest, what technical and social components support the operation, and how they relate. The ideal data to fill in this block diagram is data sourced from field visits directly to the port. Other data alternatives that can be used are documents sourced from official bodies (port authorities) to ensure that the diagram that will be made later will accurately describe port operations and their components.

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[6] An asterisk (*) indicates that the analysis is specific to ports in an archipelago context.

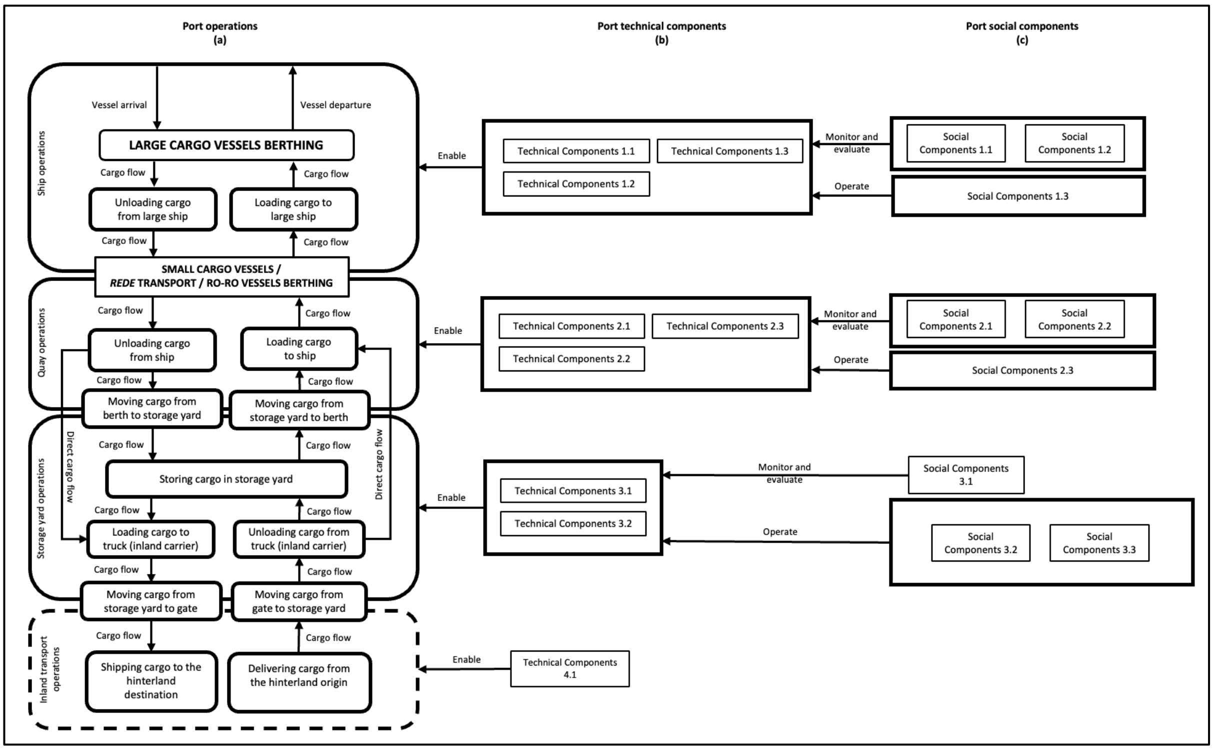

Figure 12. A customized block diagram to analyze port operations and its components as a socio-technical system.

Analyzing the island's ports-hinterland network connectivity

The analysis of ports-hinterland network connectivity in this study aims to understand the context of how island *j* can utilize the capacity of alternative ports *p* if port *d* experiences disruption due to disaster. The quality of the network on an island determines whether it can support or become a barrier to the resilience interventions of the disrupted port (i.e., mobilize heavy equipment to repair ports) or the islands' local communities. The concept of vertex reachability in graph theory is adopted to analyze the connectivity of the ports-hinterland network at island *j*.

Vertex reachability is the ease of access to a vertex from another vertex within the network (Williams & Musolesi, 2016). In the case of ports as vertices, ports with well-maintained highways linking them to other ports demonstrate higher reachability than ports with limited or poorly maintained road access. This study uses the term port reachability to describe a vertex as a port. Port reachability from other ports offers insights into alternate trade routes and potential redundancy within the hinterland network, which can be utilized during emergencies. This diversification of routes reduces dependence on a single access point and enables ports to effectively receive support after being affected by a disaster.

Furthermore, reachability from other ports promotes resource sharing and collaboration among ports. During crises or emergencies, ports can provide mutual assistance by sharing resources and services, leveraging their resilience. Estimating port reachability from other ports provides an understanding of the extent of a port's and island's resilience potential under disruptive events. The initial step before calculating port reachability is to quantify the sufficiency of the available spare capacity at alternative ports *p* against the need to substitute the capacity loss of the disrupted port *d*.

To calculate this sufficiency, the analysis focuses on the network's vertex part by calculating the available spare capacity of the alternative ports p on island j, SC_p, compared to the capacity required by the disrupted ports, SC_d. The value SC_p can be determined by subtracting the maximum capacity of alternative port p in loading and unloading cargo or passengers from the actual loading and unloading capacity used at alternative port p under normal circumstances. Meanwhile, the value of SC_d can be determined by calculating how much capacity is lost from disrupted port d, which is then used as a reference to be substituted by other ports. This study proposed a metric called *"Spare capacity replacement index"*, $SCRI_p$, to measure the sufficiency percentage of spare capacity available at other alternative ports p. The units that can be used depend on the type of ship being served, whether it is a container ship (units in TEUs), general cargo (units in DWT), or a passenger ship (units in person). $SCRI_p$ indicates what percentage of spare capacity is available at other alternative ports p on island j, if the disrupted port d is shutting down by a disaster or other disruptive events. The formula for calculating $SCRI_p$ is presented in Equation (1),

$$SCRI_p = \left(\frac{SC_p}{SC_d} \right) \times 100\% \qquad (1)$$

Where:
SC_p = Spare capacity available at alternative port p [TEU or DWT or person]
SC_d = Total spare capacity needed by the disrupted port d [TEU or DWT or person]

Thus, to estimate the reachability of a disrupted port d from all other alternative ports p on island j, this study proposes the "*number of inland transport (trucks, railway, or barges) resources required per day to utilize the spare capacity of alternative ports at the given period of t"*, or $N_p(t)$ as a main metric. The formula for calculating $N_p(t)$ is described in Equation (2).

$$N_p(t) = \sum_{p=1}^{P_j} \frac{\left(SC_p \times \min dt_p \right)}{24 \times \alpha} \qquad (2)$$

Where,
SC_p = Spare capacity available of alternative port p at island j [TEU or DWT or person]
dt_p = Shortest time spent on round trip from alternative port p to disrupted port d [hour]
α = Adjustment factor of inland transport modes

$N_p(t)$ represents the ease of access between the disrupted port and the alternative port used on an island measured by how much inland transportation resources are required to deliver the cargo. To calculate $N_p(t)$, it is first necessary to identify the spare capacity available for each alternative port p used to back up the loss of capacity of the disrupted port d on island j, or SC_p . Once SC_p is calculated, the fastest travel time of the selected land transportation mode to deliver round-trip cargo from alternative port p to the disrupted port d, or min dt_p is calculated.

In determining dt_p, this study also considered the truck driver's rest time. The product of SC_p and dt_p indicates how sufficient and easily the disrupted port accesses the available spare capacity at alternative port p. This product is divided by 24 hours multiplied by the adjustment factor α of the selected inland transportation mode. For example, if the SC_p is calculated in TEU units, then if it is assumed that the land transportation mode used is a container truck with a capacity of 2 TEU, the value of α is 2. $N_p(t)$ is then calculated by summing up all the resources used to access the selected alternative port p until the capacity loss at the disrupted port d is fully replaced. This $N_p(t)$ value will be useful in estimating how many inland transport fleets must be available on the island. The higher the gap between the availability of inland transport fleet on an island and the value of $N_p(t)$ indicates that when a port is disrupted, it becomes increasingly difficult to utilize the capacity of alternative ports on the island.

Analyzing the island's shipping network connectivity

The island's shipping network connectivity analysis aims to find out how the connectivity of an island with other islands. The port on an island becomes an enabler of connectivity from one port to another and makes the island not isolated. The island's connectivity conditions to other islands need to be analyzed to make evaluating port resilience and its impact on island connectivity clearer. In this research, the definition of island connectivity used is based on the works of Lekakou et al. (2021), which mentions that connectivity is the availability of transport that enables people and goods to travel to their destination.

To analyze the island's connectivity, this study uses metrics adopted from calculating vertex strength in complex network analysis (Liu et al., 2018; Rousset & Ducruet, 2019). Vertex strength quantifies how much of a vertex (port) is directly connected to other vertices in a network by summing up all absolute edge weights (shipping frequency) of edges connected to the given vertices (shipping routes) in a given period (i.e., 6 months or 1 year). Based on the vertex strength metric, this study proposes a metric to quantify the Connectivity of port i in Island j in a given period of time, *t*, $C_{ij}(t)$, which shows how central port i is in island j in the given period of time *t*. The units that can be used depend on the type of ship being served, whether it is a container ship (units in TEUs), general cargo (units in DWT), or a passenger ship (units in persons). The formula to calculate $C_{ij}(t)$ is shown in Equation (3). Thus, this study evaluates the island's shipping network connectivity at the given time *t*, $IC_j(t)$, by summing all the values of C_{ij}(t), as shown in Equation (44).

$$C_{ij}(t) = \sum_{k=1}^{K_j} \left(S_{ijk} \times F_{ijk} \right) \qquad (3)$$

Where,
$C_{ij}(t)$ = Connectivity of port i on Island j for the given time period t [TEU or DWT or person]
K_j = Total number of all ships that visit Island j
S_{ijk} = The total shipping capacity[7] of ships k at the port i on the Island j [TEU or DWT or person]
F_{ijk} = Visiting frequency of ships k at the port i on the Island j

$$IC_j(t) = \sum_{i=1}^{M_j} C_{ij}(t) \qquad (4)$$

Where,
$IC_j(t)$ = Island's shipping network connectivity at the given time t [TEU or DWT or person]
M_j = Total number of all ports on the Island j
$C_{ij}(t)$ = Connectivity of port i on the Island j for the given time period t

The activity continues by identifying the available shipping services (as ends in the shipping network) associated with the port under study to gain further insights. This analysis aims to understand where the shipping service connections originate and where the shipping from the port is headed. This analysis aims to identify critical shipping service connections to the port, one of which is characterized by the largest available shipping capacity between one port and another. The result will be useful later in analyzing the dynamics of shipping service connections when port operations are disrupted and how other alternative ports on the island can handle the diverted flow of shipping service.

3.2.2 Phase 2: resilience curve analysis

The second phase of the method focuses on evaluating port resilience based on past events through resilience curve analysis to operationalize the measures of resilience performance (M block in theoretical framework). Constructing a resilience curve in this phase measures the port's performance and behavior during different stages of a resilience cycle.

The construction of a resilience curve is crucial for several reasons. Firstly, it allows stakeholders to assess the overall resilience of the port system by evaluating its performance in various phases of the disruption. The curve visually represents how the port's operations evolve throughout the disruption event, highlighting patterns, trends, and fluctuations in performance indicators. By analyzing and mapping the port's performance indicators over time, the resilience curve provides valuable insights into the port's ability to withstand, respond to, recover from, and adapt to disruptions. Secondly, the resilience curve aids in identifying critical events and

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[7] The meaning of 'capacity' here is the theoretical maximum capacity of port-visiting and port-leaving vessels at port i on island j, which can be measured in TEU for container vessels, DWT for non-package vessels, or number of people for passenger vessels.

milestones during the disruption. By analyzing the curve, stakeholders can pinpoint specific moments or operational changes significantly impacting the port's performance. These critical events serve as reference points for understanding the triggers or factors influencing the port's response and recovery efforts.

To construct the resilience curve, a data-driven analytical approach is used to obtain an accurate resilience curve. The first step to creating a resilience curve is to determine what indicators measure the port's performance during a resilience cycle to be mapped on the resilience curve. Once the primary indicator is determined, data is then collected to map the indicator's behavior over time. There are several data sources commonly used to map port performance indicators. The first is data from AIS (Automatic Identification System), which contains real-time ship movements and visits to the port. AIS data helps investigate the port's performance based on sea traffic activity. However, since AIS does not cover many small ports in the archipelagos, another alternative data that can be used is data from the information system installed in the port. However, port performance data is often recorded manually in very small ports and requires access to internal port call records to construct a resilience curve.

The performance data collected from those sources is then plotted to form the resilience curve. In other words, a resilience curve constructed in this phase is a graphical representation that visualizes the changes in a port's performance over time (Varlamov et al., 2020). This study uses the daily data range from the three alternative data sources above to develop the resilience curve. If there are high fluctuations in the daily data during the resilience curve formation process, this study uses the x-day average technique to make the curve smoother. Daily high-performance fluctuation generally occurs in small ports in the outermost and remote areas. For example, in one week, there are days when ship visits are busy, but there are other days when the ships are not there. For this reason, plotting using the *x*-day average is chosen. *x* represents the variable number of days determined to produce the average value at the port. Take, for example, the *x* value taken is 3 to represent that one point on the resilience curve is the average port performance value for 3 days, then the formula used to plot the resilience curve is described in Equation (5) as follows:

$$\bar{P}(t) = \frac{P(t) + P(t-1) + P(t-2)}{3} \qquad (5)$$

Where:
$\bar{P}(t)$ is the average port performance value[8]
$P(t)$ is the selected port performance indicator at time t
$P(t-1)$ is the selected port performance indicator at time $t-1$
$P(t-2)$ is the selected port performance indicator at time $t-2$

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[8] This variable depends on the indicator used to measure the operational performance of the port. In this study, the indicator used is the operational productivity of the port in serving ships which measured by its maximum theoretical capacity. The indicator used are Container Vessel Capacity (in TEU), Cargo Vessel Capacity (in DWT) for general cargo ports, and Passenger Vessel Capacity (in person) for passenger ferry ports.

Once the curve is constructed, the critical change points and new stable state points on the empirical resilience curve can be identified to determine the four resilience phases: preparedness, response, recovery, and adaptation, as well as resilience attributes. To divide these four phases, it is necessary to determine the crucial time points that will be used as the basis for *changepoints*, which will be the transition points between one phase and another. In addition, it is also necessary to establish new stable state points on the curve that show whether the port performance is still in the same phase.

To operationalize these changepoints and new steady state points, this study uses the standard deviation of the average port performance under a particular period, σ, as a boundary to determine whether a point becomes a changepoint. A point on the curve is determined as a changepoint if the delta between port performance at time *t,* $P(t)$, and the performance at the next step, $P(t+1)$ is more than or less than σ (> σ or < σ). Meanwhile, the new stable state points are set at the first point $P(t)$ if within the performance range from $P(t)$ to the next changepoint, $P(t+n)$, and the performance change is within the normal standard deviation range. Using this procedure, the resilience curve will always have 2 types of change points and 2 types of new stable states, which are explained as follows:

- $\boldsymbol{t_e}$ **(*time of event*, changepoint)** = Represents the point on the resilience curve at which a disruption occurs, and the point at the next timestep indicates a performance degradation that exceeds the σ limit under normal conditions.
- $\boldsymbol{t_d}$ **(*time of disrupted*, new stable state point)** = Represents the residual performance point resulting from the impact of an event that causes port operations to be significantly degraded.
- $\boldsymbol{t_s}$ **(*time of shift*, changepoint)** = A point on the resilience curve that marks a positive or negative performance change that is more or less than σ in the next time step.
- $\boldsymbol{t_f}$ **(*time of fixed*, new stable state point)** = This is the starting point of the new stable port performance, where from this point to the next changepoint, the standard deviation of the average performance is still within σ.

The four phases of resilience on the curve are divided based on the points above, followed by the following division. For further explanation of what is meant by each resilience phase, please refer to Chapter 2 in the theoretical foundation section:

- **Preparation phase** $[\boldsymbol{t} < \boldsymbol{t_e}]$, is a phase where port performance shows the behavior before being affected by disruptive events (i.e., natural disasters).
- **Response phase** $[\boldsymbol{t_e}, \boldsymbol{t_s}]$ **or** $[\boldsymbol{t_d}, \boldsymbol{t_s}]$ is the phase where the port performance shows the behavior after being affected by the event at time *t*, t_e, or since being in the lowest residual performance point, t_d until changepoint t_s. The choice between t_e or t_d can be adjusted according to the type of disruption or natural disaster. For example, tsunamis have a short duration but generally have a very high level of destruction. It is very difficult to respond at the point of t_e so that the new response phase can be started from t_d. Meanwhile, for other types of disasters such as tropical

cyclones that can occur for days and have a predictable trajectory, the response phase can start from point t_e.

- **Recovery phase $[t_s, t_f]$** is the resilience phase that starts from the changepoint when the port performance is still below normal, t_s (has not returned since being disrupted), until it reaches a new stable point equal to the normal port performance before being disrupted.
- **Adaptation phase $[t > t_f]$** is the resilience phase that begins when the new stable state point has reached a normal condition like before the disruption.

Expert judgment from key port stakeholders can also be added to validate the constructed resilience curve and ensure the results are accurate and representative of the real world. Their assessment of the timing and nature of phase transitions can help produce a more precise phase division in the port resilience curve and a high confidence level. Port resilience attributes can be assessed once the constructed curve has a high confidence result. Assessments related to port resilience attributes using validated resilience curves can be made based on performance-based, time-based (duration), or both dimensions. The list of resilience attributes, metrics, and theoretical formulas for operationalizing these attributes are described in Table 3.

Table 3. Operationalization of the resilience attributes proposed in this study

Resilience attributes	Metrics and theoretical formula	Dimension	Explanation
Robustness	Average residual performance per day from t_d to t_s, $f(t_d)$/day	Performance-based	Robustness describes the average remaining performance level (*residual performance*) following the disruptive event, from t_d to t_s
Vulnerability	Average depth of performance decline from t_d to t_s, $[f(t_0) - f(t_d)]$/day	Performance-based	Vulnerability is the ability of a port to withstand disruption, which can be measured by calculating the average *depth of impact,* subtracting the port performance under normal conditions $f(t_0)$ by the residual performance $f(t_d)$, from t_d to t_s
Responsiveness	Duration of time spent at response phase $(t_s - t_d)$ or $(t_s - t_e)$	Time-based	Responsiveness describes the duration spent in the disrupted state to react, gather resources, and devise strategies to start the performance recovery.
Rapidity	Duration of time spent at recovery $(t_f - t_s)$	Time-based	Rapidity describes how fast the duration of time spent on the recovery process from a time when the performance is in a degraded state, $f(t_d)$, to a new stable performance level $f(t_f)$.
Recoverability	Speed of recovery, $\frac{df(t_s)}{dt}$	Performance and time-based	Recoverability describes how system performance changes over time in the recovery phase.

The primary output of this phase is an accurate resilience curve, which graphically represents the port's performance over time during the four phases of the resilience cycle. It visually displays fluctuations, trends, and patterns in port performance indicators, offering a comprehensive view of how the selected port's operations performance evolves before and after the disruption event. Another output of this phase is the assessment of the port's resilience attributes. These outputs serve as a basis for the next phase of port resilience evaluations.

3.2.3 Phase 3: disaster impact analysis

As discussed earlier, resilience curve analysis focuses on examining the behavior of port performance throughout different stages of the resilience cycle. Based on this understanding, the subsequent phase involves conducting a disruption impact analysis. This phase tries to understand the effects and consequences of disruptions on the system. It zooms in on how exogenous uncertainties (X) produce particular effects and consequences for the system relationship (R).

This phase focuses on assessing the direct impact of disruptions on the port infrastructure and the port-hinterland network of the islands and the indirect impact on the maritime connectivity of the islands. What direct impact means is that it causes changes in the infrastructure due to the natural disaster. Meanwhile, indirect impact means the impact that occurs due to the disruption of the port on the island. The direct impact analysis focuses on what happens at the point t_d[9] on the resilience curve. Meanwhile, the indirect analysis focuses on the range of response phases ($[t_e, t_s]$ or $[t_d, t_s]$) and the recovery phase ($[t_s, t_f]$) on the resilience curve.

Analyzing the direct impact of disasters on port socio-technical components

At the port level, the analysis provides a detailed evaluation of the damage incurred by the port area's physical infrastructure, facilities, and operational systems. It examines the extent of structural damage, provides an explanation of equipment functionality, and explains disruptions to the regular operations workflow. Technical reports, press archives, and interviews are used to analyze the consequences faced by the port after disruptions. Qualitative codification of this data provides insights into the technical and social components affected by natural disasters. The analysis provides a detailed evaluation of the damage incurred by the port area's physical infrastructure, facilities, and operational systems.

The impact analysis includes direct and indirect impacts of disruption. For the direct impact, the analysis focuses on investigating the condition of the social and technical components of the port after the disruption at point t_d. As for the indirect impact, the analysis focuses on identifying whether the disruption of ports-hinterland connectivity on the island affects the socio-technical components of the port in the response phases ($[t_e, t_s]$ or $[t_d, t_s]$) and the recovery phase ($[t_s, t_f]$) on the resilience curve.

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[9] Please refer to Figure 5 in the previous chapter for more details about the meaning of time t_d

To operationalize the analysis in this section, this study proposed a tool, namely the Port Infrastructure Damage Assessment (PIDA) sheet. The PIDA sheet consists of four columns that need to be filled in: **P**ort Infrastructure Components, **I**nfrastructure Degree of Damage, **D**amage Condition, and **A**nticipated Recovery Time, which, when abbreviated, is also PIDA. The PIDA sheet was developed based on the Infrastructure Damage Assessment (IDA) methodology used by the United Nations Development Program (UNDP, 2022). IDA is a methodology used to assess the operational status and level of damage to the public infrastructure. IDA groups the level of damage to infrastructure into three categories, namely:

- ***Totally Damaged (T)***. This signifies that the infrastructure has suffered complete damage, is unusable, and is entirely non-functional. In some cases, the totally damaged infrastructure poses some dangers to the surrounding environment, as they are liable to collapse and contain a large amount of rubble and construction debris.
- ***Partially Damaged (P)***: The infrastructure is still operational but cannot deliver its full capacity.
- ***Undamaged / Operating Normally (N)***: This indicates that the specific component can function normally even after being impacted by a disaster.

In the PIDA sheet, we adopt the categorization above to assess each port's infrastructure component, both technical and social, with an additional explanation of the damage condition. PIDA sheet consists of four main columns. The first column on the left lists all the technical and social infrastructure components of the Port that have been grouped into the four main operations of the port, i.e., ships, quay, storage yard, and inland transport operations.

The second column contains the assessment results related to the level of damage experienced by each of the main supporting components of port operations qualitatively, whether it falls into the T, P, or N category. This column contains the damage condition as the justification for the damage category given. The fourth column is recovery time, which contains the date and duration of the component returning to its status from T or P to N. An illustration of the PIDA sheet can be seen in Figure 13. Alternative data that can be used to complete the PIDA include data sourced from official records, mass media articles, and focus group discussions with port stakeholders.

After the interim assessment results using PIDA are completed, the next step is to map the assessment results into the block diagram constructed in Phase 1. By plotting the analysis results from PIDA onto the block diagram, the linkages between port operations and the affected social and technical components can be more clearly identified. This makes it easier to find out what components cause port operations not to run properly. The assessment helps to identify which components require immediate attention and investment for recovery and future resilience planning.

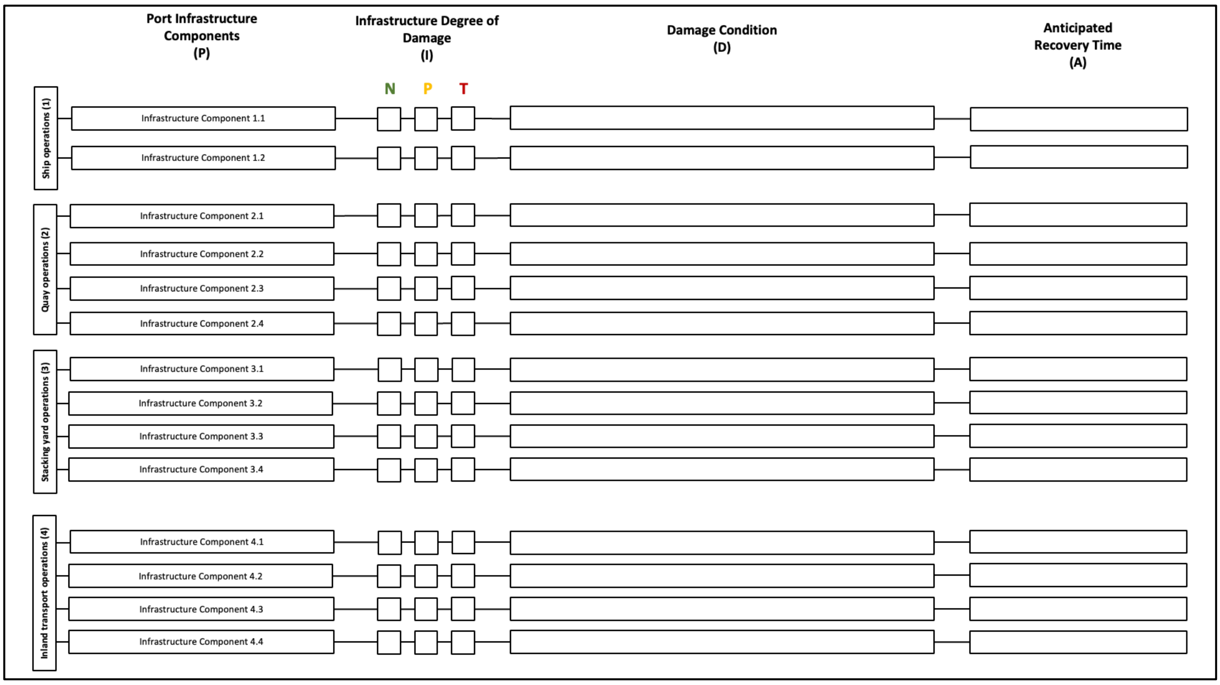

Figure 13. Visual illustration of the Port Infrastructure Damage Assessment (PIDA) sheet

Analyzing the direct impact of disruptions on the Island's ports-hinterland network connectivity

The next analysis focuses on the direct impact on the island's ports-hinterland network connectivity. There are two things to analyze in this section. The first is the direct impact of disruptions on the availability of spare capacity at alternative ports or changes in $SCRI_p$. This analysis is important because a single disruption event can affect more than one port (multi-port). The second thing analyzed is the direct impact of disruptions on the hinterland infrastructure that connects ports, thus changing the number of transport resources needed to connect ports on an island represented by $N_p(t)$. This analysis is also important, considering that some disasters have an area-wide impact, such as earthquakes, which can cause landslides and close roads that connect ports on an island.

The procedure is similar to that mentioned in Phase 1. Equation (1) and Equation (2) are reused to determine how the direct impact of a disruption affects port reachability. This analysis recalculates $SCRI_p$ and $N_p(t)$ at time point t_d on the resilience curve. The possible data used to calculate changes in $SCRI_p$ and $N_p(t)$ are taken from secondary data in the form of official reports from state agencies, field study reports from independent research groups and mass media articles. The analysis results from this section will be able to provide an impact of how much impact a disruption has on the ports-hinterland network of an island and how it affects port operations indirectly.

Analyzing the indirect impact of the Island's shipping connectivity

The last analysis in this phase analyzes the indirect impact of disruption on the island's shipping connectivity. This impact is indirect because it results from the disruption of port operations directly affected by natural disasters. The procedure used is the same as the procedure in Phase 1, which is to calculate Island shipping connectivity but in the period after the disruption, specifically in the response phases ($[t_e, t_s]$ or $[t_d, t_s]$) and the recovery phase ($[t_s, t_f]$) on the resilience curve. Equations (3) and (4) were reused to quantify the indirect impact of the disruption on the Island's shipping connectivity. This analysis then continues to identify how the changes in inbound and outbound links are connected between the affected ports and ports on other islands.

3.2.4 Phase 4: Resilience Intervention Analysis

In this phase of the method, the focus is on understanding what strategies or initiatives were taken that explain the behavior of the resilience curve of the port of interest. It aims to answer questions about how the ex-ante (pre-disruption) mitigation and ex-post (post-disruption) adaptation strategies (zooming in on the Policy Levers, L from the theoretical framework) have impacted the port operations performance behavior, especially after being affected by the disruption. The ultimate goal is to explore the options that port stakeholders have pursued to enhance port resilience in these challenges, focusing on analyzing the Policy Levers L1 and L2 from the theoretical framework.

Given the specific island factors and the archipelago setting, it is crucial to include an investigation of the initiatives taken to improve the island's spatial network connectivity, focusing on the L2 levers of the theoretical framework. Examining L2 is critical because the island's spatial factor can enable or hinder the implementation of port resilience strategies (L1). However, this study limits the analysis of L2 to the time after the disruption, or, in other words, the ex-post adaptation strategies. This limitation is used because the first layer of port actors often has insufficient authority to decide ex-ante mitigation strategies for enhancing island connectivity or port reachability.

Qualitative research techniques, such as content analysis, remote surveys, and interviews, are employed to conduct this analysis. This technique examines various information sources, such as technical reports, press archives, and expert judgment. The collected data will be organized based on the time sequence of the interventions. The collected data is then classified into the phases of the resilience cycle: preparation phase ($t < t_e$), response phase ($[t_e, t_s]$ or $[t_d, t_s]$) , recovery phase ($[t_s, t_f]$), and the adaptation phase ($t > t_f$).

3.3 Testing the port resilience evaluation method in real-world applications

Testing the port resilience method in various real-world ports and disaster scenarios allows us to assess its potential applicability and adaptability to various port contexts. Large-scale archipelagos typically consist of diverse ports, such as container, bulk, and passenger ports, each with unique characteristics. Factors like geographical location, operational scale, and business model also shape their unique characteristics. Moreover, ports face various threats, including natural disasters like earthquakes, tsunamis, floods, and tropical cyclones. By testing the port resilience evaluation method across different types of real-world ports facing varied disasters, we can determine the extent to which the method is universally applicable and adaptable, regardless of port type or disaster type. The following section presents the strategy and justification this study used to select case studies. The next section also presented an overview of each case study chosen to test the method in a real-world application context.

3.3.1 Ports in the Indonesian Archipelago as central case studies

This research focuses on the Indonesian archipelago as the central case study. The selection of Indonesia as a central case study is driven by two main reasons. First and foremost, Indonesia stands out as one of the largest archipelago countries globally, covering an area of approximately 9.8 million square kilometers. The archipelago comprises more than 17,508 islands, with a land area of 1.9 million square kilometers, while the rest is sea territory (BPS, 2019). Managing Indonesia's maritime network is a highly complex task due to the presence of over 112 commercial and 400 non-commercial ports, as well as a fleet of more than 10,000 national shipping vessels encompassing various types, such as containerships, general cargo vessels, bulk carriers, and passenger or Ro/Ro vessels.

Another reason for selecting Indonesia as the central case study is its potential risks to natural disasters, including hydro-meteorological and geophysical events. Indonesia lies within the Ring of Fire and has 127 volcanoes, representing approximately 13% of the world's active volcanoes. In 2021, the Indonesian National Board for Disaster Management (BNPB) released a multi-hazard disaster risk index for each province (BNPB, 2022) as depicted in Figure 14.

As depicted in Figure 14, many regions are classified as high-risk or very high-risk areas (colored red). The red zone signifies regions that each experience more than 144 natural disasters in a year. Djalante and Garschagen (2017) highlight that earthquakes (including tsunamis), ground movements, and volcanic activity are the most devastating and challenging natural disasters to predict in Indonesia. As a result, ports in Indonesia must be well-prepared to cope with unexpected disruptions, making the country a fitting choice as the central case study for this dissertation.

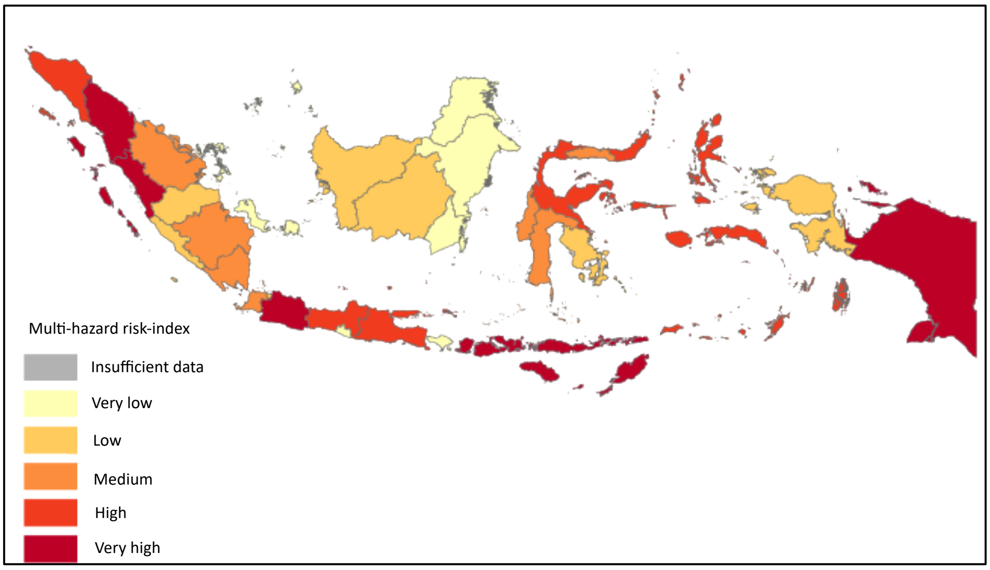

Figure 14. The multi-hazard risk map of the Indonesian Archipelago (BNPB, 2022)

Additionally, the selection of Indonesia as the central case study is influenced by the projected increase in natural disasters that will impact ports in the future. Lam and Su (2015) analyzed disruptions in Asian ports and estimated the likelihood of recurrence based on data dating back to 1900. Their findings revealed a significant upward trend in disruptive events, with natural disasters emerging as the primary cause of port disruptions and posing the greatest severity regarding vessel traffic impact.

Izaguirre et al. (2020) sought to validate this observation by analyzing historical global risks across 2,013 ports worldwide and assessing their impacts under a high-end global warming scenario. Their research indicated that ports in the Pacific Islands, Caribbean Sea, and Indian Ocean have an extremely high risk for severe disruptions by 2100. Specifically, Indonesia ranked among the top three countries facing an extremely high climate risk concerning port operations. These findings imply that Indonesia can expect a higher frequency of meteorological disasters, such as tropical cyclones, coastal flooding, and extreme weather events, in the future. With the anticipated rise in disruptive events, it is crucial to be adequately prepared to prevent disruptions from escalating. Therefore, Indonesia is a relevant and significant central case study in this dissertation.

3.3.2 The strategy of case study selection

Before selecting case studies, defining the term "case study " is essential. The term is widely recognized as ambiguous, encompassing diverse research designs (Gerring, 2004, 2007). In this dissertation, we adopt a specific and focused definition of a case study: *an intensive analysis employing quantitative, qualitative, or mixed-method approaches that investigates a single unit or a small number of units* to understand a population of cases (Gerring, 2004). Specifically, this study targets ports within large-scale archipelagos whose operations were affected by natural disasters as our initial list of potential cases.

Several past events candidates that caused port operations to be disrupted have been screened across Indonesia between 2018 and 2021. The starting timeframe of 2018 is used because the online port information system was deployed that year, making the availability of data about port calls and traffic changes easier to track. In addition, the AIS data, which is of high quality and provided by third-party services, can still be accessed for the past five years. 2018 was still in that timeframe when we started to test the method at the beginning of 2022. Five natural disasters significantly affected port operations in Indonesia. These disasters include the Central Sulawesi Earthquake and Tsunami in 2018 at the Port of Pantoloan, the Tropical Cyclone Seroja in East Nusa Tenggara in 2021 at the Port of Seba, the West Sulawesi Earthquake in 2021 at the Port of Simboro Mamuju, the Semarang Coastal Flooding in 2018 at the Port of Tanjung Mas Semarang, and the Lombok Earthquake in 2018 at the Port of Kayangan Lombok.

This study chooses the so-called *diverse case selection strategy*, following the advice of Seawright and Gerring (2008) in the case study selection. The main objective of this strategy is to ensure a wide range of variation among the case studies along relevant dimensions. By incorporating diverse cases, this study strives to achieve a comprehensive representation of the population under investigation, thereby enhancing the overall representativeness of the study (Seawright & Gerring, 2008).

The diverse case selection enables the researcher to assess the generalizability of the evaluation method. By testing the method in multiple cases that represent different characteristics and contexts, the researcher can determine the transferability and applicability of the proposed method to evaluating port resilience across various ports. This testing helps develop robust methods to evaluate the resilience of different port types in other geographical locations and under varying conditions.

Table 4 shows the comparison results of the five potential events of port disruptions caused by natural disasters in Indonesia across nine criteria between 2018 and 2021. From these events, the three case studies used in this study for further evaluation are (1) the Port of Pantoloan, (2) the Port of Seba, and (3) the Port of Mamuju Simboro. The main reason for not selecting the other two port cases is to reduce the similarity of the context with other ports (i.e., the characteristics of Tanjung Mas Semarang port are already represented by the characteristics of Pantoloan Port) so that it is expected that the ports used in the case studies are more varied.

Table 4. Comparison of case studies' characteristics that potential for this study (highlighted part is the selected case studies)

Criteria	**Port of Pantoloan**	**Port of Seba**	**Port of Simboro**	**Port of Semarang**	**Port of Kayangan**
Main function	Container cargo	Multi-purpose	Passenger	Container cargo	Passenger
Major Shipping network	Commercial	Non-commercial	Mixed (commercial and non-commercial)	Commercial	Non-commercial
Port hierarchy	Main port	Feeder port	Collector port	Main port	Feeder port
AIS Data Availability	√	-	-	√	√
INAPORTNET Data availability	√	√	-	√	-
Disaster report accessibility	√	√	√	-	-
Port operator	State-owned enterprise (PT. PELINDO)	Ministry of Transport (KUPP Kelas III Seba)	State-owned enterprise (PT. ASDP Indonesia)	State-owned enterprise (PT. PELINDO)	Ministry of Transport (KUPP Kelas III Kayangan)
Disaster event	Sulawesi Earthquake and tsunami 7.5 Mw (28 September 2018)	East Nusa Tenggara Tropical Cyclone Seroja 102 km/h (6 April 2021)	West Sulawesi Earthquake 6.2 Mw (15 January 2021)	Semarang Coastal Flooding (22 November 2018)	East Lombok Earthquake (20 August 2018)
Disaster type	Geological disaster	Meteorological disaster	Geological disaster	Meteorological disaster	Geological disaster

Case Study 1: Pantoloan Port after Central Sulawesi Earthquake and Tsunami (2018)

The Port of Pantoloan holds a critical position among the three main ports in Sulawesi, alongside the Port of Makassar in the south and the Port of Bitung in the north. Its primary role is to connect the eastern and western regions of Indonesia. The Port of Pantoloan specializes in facilitating commercial cargo transport, particularly in the form of containers. Most shipping services connected with this port serve connecting hub ports in the western-central and central-eastern parts of Indonesia, besides several services that distribute cargo to the feeder port around Pantoloan. In short, Port of Pantoloan primarily serves hub-hub and hub-spoke connection shipping services. It ranks as the third busiest port in Sulawesi in total tonnage. Under normal conditions, it can handle over 150,000 twenty-foot equivalent units (TEUs) per year. The five-year average for cargo throughput, including containers, is 1.3 million metric tons.

On September 28, 2018, seven major earthquakes struck the island of Sulawesi within a time period of 7 hours, specifically in the Central Sulawesi province of Indonesia. These earthquakes had magnitudes ranging from 5.7 to 7.5 on the Moment Magnitude Scale (Mw). The most significant earthquake, with a magnitude of 7.5 Mw, occurred at 10:02 UTC at a depth of 10 km. Its epicenter was located in the mountainous Donggala Regency, Central Sulawesi. This earthquake was approximately 70 km (43 mi) from the provincial capital, Palu. The earthquake's impact was felt as far as Samarinda in East Kalimantan and Tawau, Malaysia. Figure 15 shows the locations of the earthquake epicenter, the Port of Pantoloan, and Palu City.

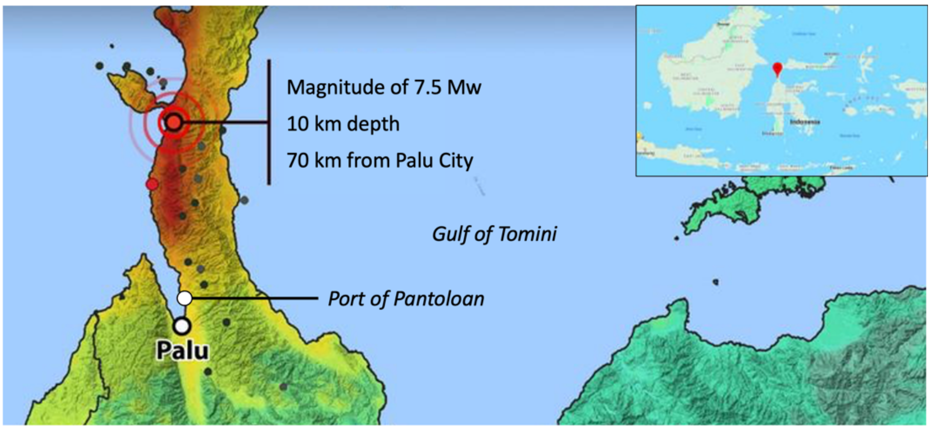

Figure 15. The location of the earthquake epicenter, Port of Pantoloan and Palu City (BMKG, 2018)

Before the main earthquake, a series of foreshocks occurred, with the largest measuring 6.1 Mw that happened earlier on the same day at a depth of 18 km. Considering all the earthquakes, the city of Palu experienced a shaking intensity categorized as "Strong" according to the United States Geological Survey's (USGS) PAGER scale. The Global Disaster Alert and Coordination System (GDACS) issued an Orange alert for the potential tsunami threat associated with this event, predicting waves of up to 1.6 meters in height. National authorities promptly issued a tsunami warning, which was later lifted. However, a tsunami did occur along the coast, reaching as far as Palu, and media reports indicated wave heights of up to 2 meters. The Port of Pantoloan in Palu suffered significant damage from the earthquake and tsunami. The initial field survey report conducted by the Ministry of Transportation revealed massive disarray upon arrival at the port. The test of our method in this case study will be covered in detail in Chapter 4.

Case Study 2: Seba Port after Tropical Cyclone Seroja (2021)

The Port of Seba is the main gateway to and from the Sabu Raijua Regency. According to the Indonesian government's Presidential Decree 06/2017, this regency is classified as the insular area of the Sabu islands. In addition, Presidential Decree number 63/2020 classifies it as an underdeveloped region. The industry on Sabu Island is not well-developed compared to the other regions, indicating that its economic potential is yet to be fully harnessed. The Port of Seba is one of only two ports on Sabu Island, the other being Port Biu. The total land area of the Port of Seba is relatively small, at 25,961 m^2. The Port of Seba is a feeder port within the Indonesian national maritime network, serving as a main gateway for Sabu Island.

It has a berth length of 90 meters and a draft of 7 mLWS, and it can only accommodate vessels with a maximum of 2,000 DWT (Deadweight tonnage) for berthing. Vessels exceeding this limit must use smaller ships as connectors to the ports in a system known as off-shore berthing or "*rede transport*." The Port of Seba is a non-commercial port managed by the government through the Ministry of Transport, Republic of Indonesia (KUPP Class III Seba). Most shipping services connected to this port are public service obligations (PSO), mostly operated with a pendulum route pattern to visit insular islands or regions in Indonesia.

On April 4, 2021, Tropical Cyclone Seroja emerged over the Savu Sea, bordering eastern Indonesia and Timor-Leste. Taking a southwesterly course, it started moving towards the Western Australian coast, as shown in Figure 16. By April 6, 2021, at 0.00 UTC, the cyclone had traveled approximately 130 km south of Sumba Island, East Nusa Tenggara. It was displaying maximum sustained winds of 102 km/h. After the cyclone passed, the Indonesian National Board of Disaster Management (BNPB) reported a significant impact on the human population and infrastructure. The immediate aftermath in East Nusa Tenggara showed a grim picture, with 128 confirmed fatalities, 72 missing individuals, and a staggering 8,424 people displaced from their homes.

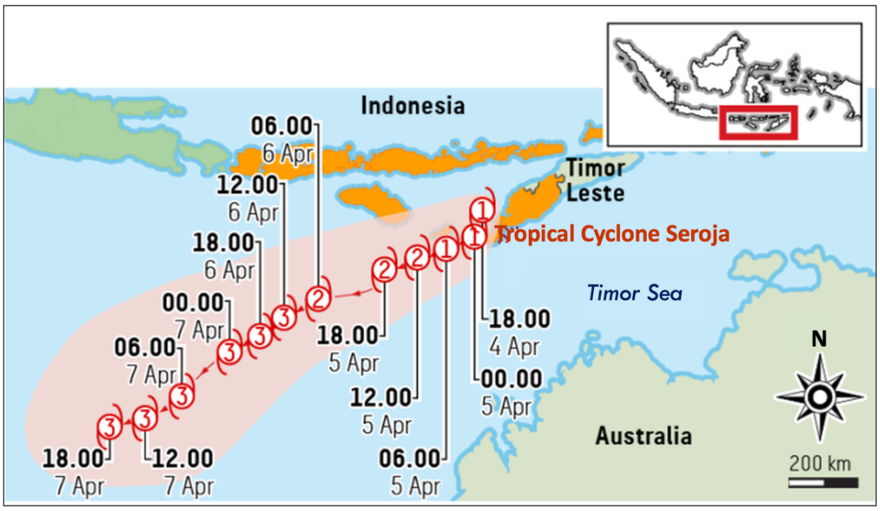

Figure 16. The illustration of tropical cyclone Seroja pathway during 4-7 April 2021 (BMKG, 2021)

By April 12, 2021, the BNPB reported that Tropical Cyclone Seroja had affected over half a million people. The recorded figures included 181 fatalities, 271 injuries, and 45 missing persons. The cyclone resulted in massive displacement, with 11,406 people left homeless. A staggering 66,036 houses sustained damage in East and West Nusa Tenggara, highlighting the destructive power of the cyclone. Besides the enormous human cost, Tropical Cyclone Seroja severely affected critical infrastructure in the East Nusa Tenggara province. The Port of Seba, located in the Sabu islands of the East Nusa Tenggara (NTT) Province, was notably impacted. On April 5, 2021, the high wind speeds caused a Ro/Ro vessel, the Cantika Express, to capsize while docked. This accident blocked the berth for cargo and passenger vessels, suspending operations at the Port of Seba. The application of the evaluation method proposed in this case study will be covered in detail in Chapter 5.

Case Study 3: Mamuju Simboro Port after Majene Earthquake (2021)

The Port of Mamuju (Simboro) is a critical passenger crossing port for West Sulawesi residents traveling to East Kalimantan, specifically Balikpapan. It accommodates vessels with a maximum deadweight tonnage (DWT) of 1,500. The passenger terminal can handle up to 600 passengers and approximately 30 vehicles. The Port of Simboro serves commercial and non-commercial shipping services managed by ASDP Indonesia Ferry LLC (PT. ASDP Indonesia Ferry). The port also operates inter-island transport services under a public service obligation scheme mandated by the central government. Furthermore, the port facilitates commercial domestic passenger liners that support inter-island passenger movement. In the regional hierarchy, the Port of Simboro is a collector port, serving as a transit hub connecting the region with other nearby ports through short-sea passenger shipping.

A powerful earthquake measuring 6.2 Mw of magnitude struck the Majene district in the West Sulawesi Province of Indonesia on 15 January 2021 at approximately 1:30 AM local time. The National Meteorology, Climatology, and Geophysical Agency (BMKG) reported that before the main quake, there was a smaller foreshock with a 3.1 magnitude, followed by six aftershocks, with the strongest aftershock having a magnitude of 4.1. Figure 17 shows the location of the earthquake epicenter. According to the National Disaster Management Agency (BNPB, 2022), the earthquake severely impacted Majene, Mamuju, and Polewali Mandar districts. The devastating event resulted in the loss of 107 lives, with 97 fatalities in Mamuju and 10 in Majene. Three people remain missing. The destruction caused extensive damage to over 15,000 houses, leaving more than 71,000 people displaced. The overall number of affected individuals reached 99,827, which included 23,248 households.

Not only did the earthquake cause substantial loss of life and displacement, but it also severely damaged critical infrastructure such as government offices, private businesses, schools, markets, and religious buildings. In Mamuju, the earthquake disrupted the operations of important facilities, including a major hospital and the Port of Mamuju Simboro, a vital passenger port. The test of our method in this case study will be covered in detail in Chapter 6.

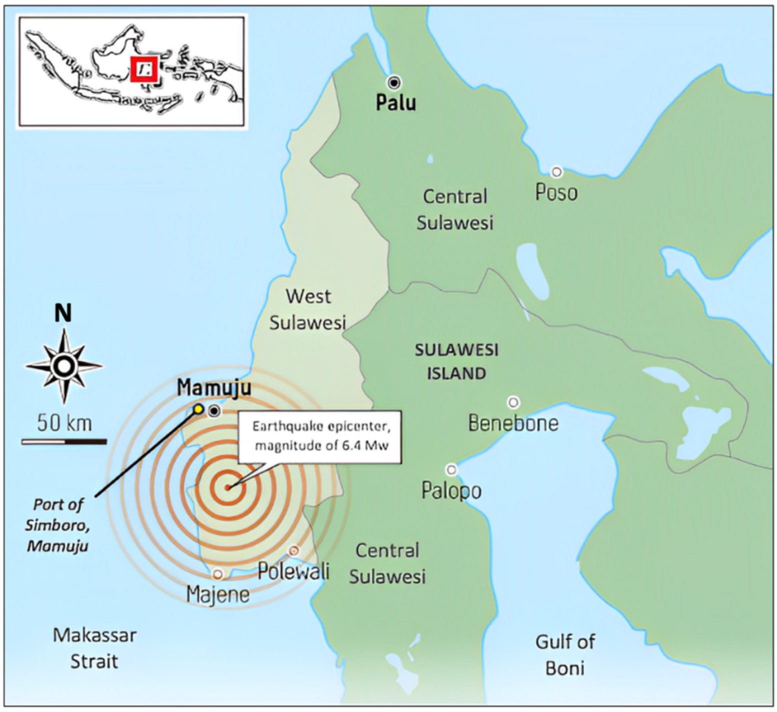

Figure 17. The location of the earthquake epicenter and Port of Mamuju Simboro (BMKG, 2021)

3.4 Evaluating the proposed resilience evaluation method

The proposed method will be evaluated and refined in the final research stage. For this evaluation, this study adapted the conceptual framework developed by Thissen & Twaalfhoven (2001) as formal guidance, which is well-suited to assessing policy analytic activities as part of a more extensive policymaking process. A policy analytic activity is viewed as an action, or a series of actions, controlled by inputs, leading to specific products or results, such as a roadmap, report, framework, method, or model. This framework is selected because this research extensively uses analytic activities, including applying the method in various case studies. This framework allows us to test whether the proposed method is flexible enough to evaluate port resilience in different contexts. Recent publications have also utilized this framework to evaluate policy evaluation methods. See, for instance, the evaluation of Traditional Chinese medicine development policies (Wang et al., 2022) and peri-urban water problems (Gomes et al., 2018, 2023).

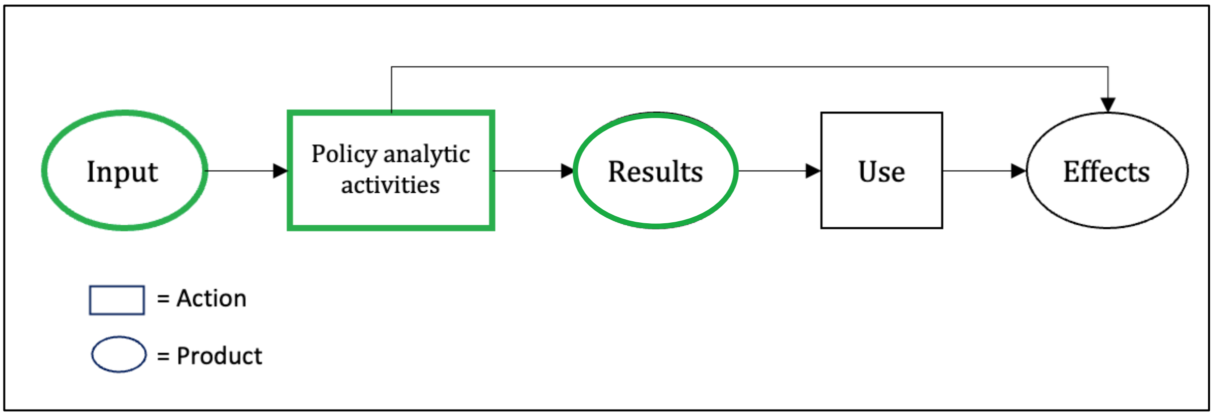

Figure 18. Criteria to evaluate policy analytic activities proposed by Thissen and Twaalfhoven (2001), with the green outline as the evaluation focus of this study

The evaluation protocol followed in this study is based on the five criteria proposed by Thissen & Twaalfhoven (2001). Figure 18 shows the conceptual structure for the criteria to evaluate the method. The conceptual structure for evaluating policy analytic activities is divided into five criteria. A brief explanation of the five evaluation criteria is presented below:

- ***Input*** concerns evaluation criteria related to aspects preceding the analysis using selected methods, e.g., why the analysis was initiated (objective) and the quality and availability of the data used in the study.
- ***Policy analytic activities*** are evaluation criteria related to the analysis process or method. For instance, the applicability of analysis methods used in each phase, the appropriateness of the case study on which the analysis was focused, and whether stakeholders' interests in the evaluation process were handled appropriately.
- ***Results*** are evaluation criteria that relate to the products or outcome of the analysis. For instance, the findings of the empirical analysis, including the presentation, relevance, and validity of the analysis results, are evaluated within these criteria.
- ***Use*** are evaluation criteria that relate to who uses which elements of the analysis for what purpose. For instance, did interest parties, decision-makers, or stakeholders use the results of the policy analytic activity successfully?
- ***Effects*** are criteria that relate to the possible effects of using policy analytic products, e.g., feeding the policy discussion, affecting the decisions taken, increasing the insights into the problem and possible solutions, improving the problem situation, or changing communication patterns.

In this study, we tailored those criteria to the context and purpose of this study. Our study focuses on developing a systematic method to evaluate port resilience in the archipelago. This study is limited to providing a systematic and scientific evaluation method for supporting policy analytic activity, not including providing policy recommendations as the result of method implementation and adapting this method for the stakeholders. This means that the evaluation shall focus on evaluating the method, not the actual implementation by stakeholders, and how the result is generated from the method proposed in the study.

Hence, the evaluation of the method is centered around the ***input, activities,*** and ***result*** as marked by the green outline in Figure 18**.** These criteria elaborate specific evaluation protocols for each intervention stage guided by a set of evaluative questions, which can be explored in more detail in Thissen and Twaalfhoven (2001). The following subsections describe the evaluation protocols used in this study for the proposed method.

3.4.1 Input evaluation

The evaluation of the method proposed in this study regarding the input criteria aims to reflect on the method's data collection. The reflection focuses on whether the quality and availability of the data are appropriate for conducting the resilience evaluation analysis in each phase for each case study analyzed in this research. The main evaluation questions are selected for the input evaluation criteria:

- Were the data collected for the analysis available?
- Was the quality of data collected for the analysis adequate?

The reason why we selected these evaluation questions is as follows. First, it is worth noting that our proposed port resilience evaluation method is derived from a theoretical perspective. We need to evaluate whether stakeholders or users have the data needed to conduct each phase of the method proposed in this study. The results of this analysis can be a recommendation regarding what kind of data must be prepared by stakeholders so that the port resilience evaluation process can be carried out quickly and effectively. The evaluation results can also show whether the data that needs to be prepared can be standardized for ports with different contexts or whether unique and different data is needed for different port case studies.

Second, data quality is crucial for conducting empirical evaluations of port resilience. High-quality data ensures that the result of port-resilience evaluation can reflect the integrity of what happened to the port-resilience based on past events. By having data quality criteria as inputs, the researcher and port stakeholders can be more confident in using the empirical result to guide decision-making in the future. In addition, the evaluation result can also reflect on which case study has high-quality or low-quality data and what suggestions this study can provide for collecting better or more appropriate data in the future. This study uses several dimensions of data quality for evaluating the data as the input, including availability, accuracy, completeness, and timeliness (see Jayawardene et al. (2013); Huang (2013)).

3.4.2 Activities evaluation

This evaluation emphasizes the method's implementation process. The evaluation of activities takes place during each of the four phases of the port-resilience evaluation method proposed in this study. The evaluation of activities is focused on the processes and methods used in the port-resilience evaluation method. In evaluating activities, each phase is evaluated separately, using the same set of criteria. The evaluation aim of the activities is (1) to identify the key enablers or barriers affecting the practical implementation of the method and (2) to assess the temporal requirements of the method's implementation process. Two main evaluation questions are selected for the activities evaluation criteria:

- Were there any major enablers or barriers identified when implementing this method?
- Were there noticable time demands during the method's implementation process?

During the activity evaluation phase, the evaluation is done by investigating how each phase and tool fits the analytical objectives. Because this evaluation is conducted using three different case studies, the evaluation result can also gather insight about (1) under what port context or circumstances the methods and tools have an advantage or weakness in analyzing port resilience and (2) whether the phases taken to conduct port resilience can be generalized across different ports in archipelagos, or whether the phases need to be customized for each port.

3.4.3 Results evaluation

The evaluation related to the result, which is the product or outcome of the analysis, is focused on the relevance of the findings of the empirical analysis to the policy makers and port operators. The relevance aspect was chosen because it is expected that this method can later be adopted and applied in the real world by the port actors, so it is important to evaluate whether the results produced by this evaluation method are relevant and useful to the main stakeholders. A main evaluation question is selected for the results evaluation criteria:

- *Did the analysis result relate to clients' (policy maker and port operator) substantive concerns and spheres of responsibility*?

The results of the evaluation are expected to show the potential usefulness of the results produced in this study. The potential usefulness will be categorized based on its usefulness for policy makers and port operators. The evaluation is separated for the two stakeholders because these two actors are the main actors authorized to enhance port resilience but have different objectives and responsibilities.

3.5 Concluding remarks

Chapter 3 set out to design a systematic method to operationalize resilience concepts and theories that could be used to support port authorities in evaluating port resilience in large-scale archipelagos. The proposed method is developed based on the theoretical framework of theories of port resilience, the island's relationality, and the complexity of port operations in the archipelago.

The proposed method consists of four main phases, each fulfilling a specific objective in evaluating port resilience. The method also considers the spatial characteristics of islands and port locations. Three case studies of port disruptions have been selected to test the proposed evaluation method. This dissertation concluded the chapter by explicitly outlining the criteria we will use to evaluate our method, which includes the input, activities, and results of the analysis. The following chapters present the method's application, evaluation, and reflection for three case studies.

4 Case Study: Port of Pantoloan

This chapter presents the first real-world case study[10] to test the empirical evaluation method for port resilience in archipelagos developed in Chapter 3. The case study concerns the Port of Pantoloan Container Terminal during Sulawesi's earthquake and tsunami disaster in 2018. Note that the choice for this disaster was already presented in Section 3.3.1 Case Study Selection. The first four sections of this chapter correspond to the four phases of the evaluation method. Section 4.1 analyzes the Port of Pantoloan's socio-technical system and Sulawesi Island's transport connectivity as a complex spatial network. This phase provides an overview of the port's context under study and the level of connectivity of the island (Sulawesi) regarding maritime and hinterland network connectivity. Section 4.2 focuses on the resilience curve analysis of the Port of Pantoloan based on the selected key performance indicators during different stages of the resilience cycle[11]. Section 4.3 analyzes the disaster impact on the ports and the Island's connectivity based on specific points in the resilience curve. Section 4.4 explores interventions and strategies at the Port and Island level that may enhance or hinder improving the resilience at the Port of Pantoloan. Section 4.5 synthesizes the lessons from the empirical analysis and how they relate to the theoretical resilience attributes. This section also provides some recommendations to improve the theoretical resilience attributes. Finally, Section 4.6 highlights the critical points from the analysis result and concludes the chapter.

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[10] The datasets used in this case study are available at https://doi.org/10.4121/3bee7025-46ad-4038-b4f9-8a406b223bfd

[11] The resilience cycle consists of four phases: preparations, response, recovery, and adaptation. Please refer to subsection 2.3.2 in this thesis for further explanation

4.1 Phase 1: Port system and island connectivity analysis

Section 4.1 is divided into three parts, each focusing on a different analysis aspect of phase 1. First, we analyze the technical and social components of the port of Pantoloan that contribute to its operational functions. A block diagram will be used as the primary analysis tool. Secondly, we describe Sulawesi Island's ports-hinterland network connectivity using quantitative metrics from graph theory. Finally, we capture the connectivity of shipping around Sulawesi Island through the use of metrics derived from graph theory and complex network analysis.

4.1.1 Analysis of Port of Pantoloan and Its Operations as a Socio-Technical System

This section analyzes the technical and social components of the Port of Pantoloan, along with their linkages that enable port operations. The primary purpose of the analysis is to understand how the Port of Pantoloan works. This subsection first presents an overview of what Pantoloan Port looked like before and after the earthquake and tsunami in September 2018. The next part of this section elaborates on the result of the analysis of the Port of Pantoloan as a socio-technical system using a Block Diagram.

Overview of Port of Pantoloan Container Terminal

The Port of Pantoloan is located in Palu City, Central Sulawesi. Administratively, the Port lies within the Pantoloan Subdistrict, Tawaeli District, Palu City. It is 23 km from Palu City. The Port of Pantoloan spans a land area of 114,980 square meters. Of the entire area, 105,330 square meters are certified land owned by PT. Pelindo IV[12], while the remaining part is under reclaim and in the certification process. The name of Pantoloan itself is taken from the subdistrict where this port is located. One of the critical facilities of this port is its container terminal. Port of Pantoloan is the largest and busiest port in the Central Sulawesi Province and serves as a trade center for the eastern region of Indonesia. The aerial view of Port of Pantoloan in 2018 before being struck by the earthquake and tsunami is depicted in Figure 19.

Figure 19. Aerial view of the Port of Pantoloan in Central Sulawesi, Indonesia (Courtesy of Ministry of Transportation, 2020)

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[12] PT Pelabuhan Indonesia IV or Pelindo IV is a (former) Indonesian State-Owned Enterprise engaged in Indonesian port operations and services.

The primary activities at the Port of Pantoloan involve loading and unloading general cargo and goods in containers, including copra, rattan, fertilizer, cement, and processed food products. The Port also handles liquid bulk cargo, such as asphalt. PT. Pelindo IV (Persero) conducts all operations at the Port of Pantoloan via a concession agreement with Harbor and Port Authority Office (Kantor Kesyahbandaran dan Otoritas Pelabuhan / KSOP) Class II Teluk Palu. The area surrounding the Port of Pantoloan is predominantly residential. To the southeast, the Pantoloan Terminal borders PT. Toloan, while to the northwest, it borders local community lands. The layout of the Port of Pantoloan in 2018 before the disaster is depicted in Figure 20.

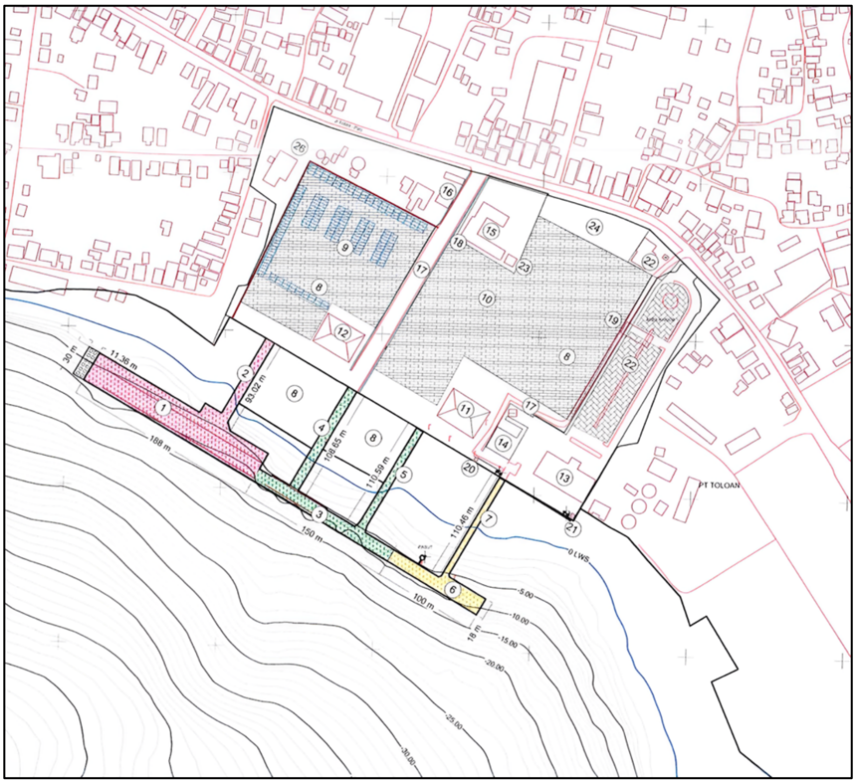


Figure 20. The layout of the Port of Pantoloan (Courtesy of Ministry of Transportation, 2019)

The Port of Pantoloan has a berth of 438 meters in total, which is divided into three segments. Segment number 1 in the figure (red color) is operated specifically for containerships. Segment number 3 (green color) serves non-containerized cargo ships. Segment number 6 (yellow color) serves both cargo and passenger ships. The data inTable 5 pertains to the other technical components supporting the operations of the Port of Pantoloan. The numbers in the table refer to the numbers in Figure 20. In addition to the port facilities described in the table, the Port of Pantoloan was equipped with container loading and unloading and general cargo handling facilities. Table 6 provides an overview of the port's specific cargo handling facilities. These facilities play a crucial role in facilitating the smooth movement of goods and contribute to the overall efficiency and effectiveness of operations at the Port of Pantoloan Container Terminal.

Table 5. Existing facilities of the Port of Pantoloan in 2018

No	Facilities	Units	Dimension	Remarks
1	Segment 1 Berth	m^2	188 x 30	This berth is intended to serve containers. The berth is owned by PT. Pelindo IV (Persero)
2	Trestle 1	m^2	93 x 10	The trestle is owned by PT. Pelindo IV (Persero) ownership lies with the Ministry of Transportation, Republic of Indonesia
3	Segment 2 Berth	m^2	150 x 13	This berth is intended to serve non-container cargo ships. The berth is owned by PT. Pelindo IV (Persero)
4	Trestle 2	m^2	108.7 x 10	The berth asset ownership lies with the PT. Pelindo IV (Persero)
5	Trestle 3	m^2	110.6 x 10	The trestle is owned by PT. Pelindo IV (Persero)
6	Segment 3 Berth	m^2	(60 x 13) + (40 x 18)	The berth is intended to serve non-container cargo and passenger ships. The berth is owned by PT. Pelindo IV (Persero)
7	Trestle 4	m2	110.5 x 6	The trestle is owned by PT. Pelindo IV (Persero)
8	The land area of Port of Pantoloan	m2	114,980	An area measuring 105,330 m2 and a reclaimed area of 9,650 m2 have been certified. These assets are owned by PT. Pelindo IV (Persero)
9	Stacking yard 1	m^2	17,500	Intended for containers
10	Stacking yard 2	m^2	28,000	
11	Warehouse 101	m^2	1,200	Intended for non-containerized cargo
12	Warehouse 102	m^2	1,200	
13	Passenger terminal	m^2	2,000	-
14	Port Authority (KSOP) office	m^2	688	-
15	PT. Pelindo IV (Persero) office	m^2	4,484	-
16	Maritime and Coastal Guard Unit (KPLP) Post	m^2	350	-
17	Port access road	m^2	564	-
18	Port security post	Unit	3	-
19	Lighthouse	Unit	1	-
20	Port security enforcement unit	Unit	1	-
21	Cafeteria	Unit	1	-
22	Parking area for passenger terminal	m^2	5,431	-
23	Truck parking area	m^2	3,016	-
24	Workshop	m^2	571	-

In addition to the technical components, our assessment also focused on identifying the social components that supported the operational aspects of the Port of Pantoloan in 2018. The relevant data for this part of the analysis was obtained through correspondence with officials from the Palu Bay Class II Harbor Master and Port Authority Office (KSOP Teluk Palu). Table 7 presents a list of personnel and their respective roles, which have been made available for this research. The social actors or components included in the analysis were limited to the first layer actors, as they play a significant role in determining the port's operations and resilience, as per the classification defined by UNCTAD (2020). This method allowed us to gain insights into the critical human factors and social elements contributing to the port's functioning and its ability to withstand disruptions effectively. Building upon the technical components and actor roles involved in port operations in Port of Pantoloan, the following subsection elaborates on how these two components (technical and social) are interconnected.

Table 6. Facilities for container loading/unloading and cargo handling at the Port of Pantoloan in 2018

No	Facilities	Number (unit)
1	Tug boat - 94 PK	1
2	Mooring boat - 40 PK	1
3	Speed boat - 2 x 85 HP	1
4	Container crane	1
5	Harbor mobile crane	1
6	Rubber tire gantry	2
7	Level luffing crane	1
8	Reach stacker 40-ton	4
9	Forklift 32 ton	1
10	Forklift 7 ton	2
11	Forklift 5 ton	1
12	Forklift 3 ton	1
13	Forklift battery	2
14	Head truck 40-ton	8
15	Chassis trailer	11

Table 7. A list of first-layer actors (social components) that support the operational aspects of Port of Pantoloan

Actors	Entities	Roles	Personnel
Port Authority	KSOP Kelas 2 Pelabuhan Pantoloan	Legal and ship certification	7
		Navigation safety, guarding, and patrol	5
		Maritime traffic and port business development	8
Port/Terminal Operator	PT. Pelindo IV (Persero)	Foreman/supervisor	10
		Crane operator	4
		Equipment handling	12
	Stevedore Labor Cooperative	Provide Stevedoring Labor	60

Port of Pantoloan as a socio-technical system

Ideally, to better understand the operations in the Port of Pantoloan, a field visit and live observations of how the Port of Pantoloan works would have been ideal. However, due to the COVID-19 pandemic, PT. Pelindo (a state-owned port operator company) only allowed us to visit a container port terminal in Tanjung Priok, Jakarta. During that field visit, an overview of how PT Pelindo manages the port and container terminal operations was presented. The explanation included the organizational structure, operational scheme, and technical and social components. From this visit, it was confirmed whether the Pantoloan Port operational system has the same characteristics or not because both are managed by PT Pelindo.

There were two port visits during this study. The first port visit took place in June 2020, and the second in July 2022. Figure 21 shows the field visit to one of the container terminals in Port of Tanjung Priok, Jakarta, in June 2020. The main agenda of the port visit was to observe how port operations take place at the container terminal and to observe the interrelationships between the social and technical components of the port operations. As described in section 3.3.1, a block diagram illustrates container terminal operations at the Port of Pantoloan, including the social and technical components involved. Three experts are invited to discuss the block diagram we developed during the visit and afterward to minimize conceptual bias. Table 8 shows the background of the experts we asked and their work experience. The field visit and discussion with experts helped to construct the Port of Pantoloan's block diagrams.

Table 8. The list of experts invited to conceptualize the Port of Pantoloan as a Socio-Technical System

Role	Institution	Years of experience
Academic/Researcher in port development and maritime logistics	Universitas Indonesia	23
Assistant Manager of Terminal Operations	PT. Samudera Terminal Indonesia	15
Staff of Maritime Transportation Research and Development Agency	Ministry of Transportation, Republic of Indonesia	9

Figure 21. The container terminal port visit with the experts

As a result of this activity, a finalized block diagram that conceptualizes the Port of Pantoloan as a socio-technical system is shown in Figure 22. In the figure, the Port of Pantoloan's operations are divided into three sections: (a) port operations at the Port of Pantoloan, (b) port technical components, and (c) port social components. The diagram explains the port operations process at the Port of Pantoloan container terminal, what technical and social components support the operation, and how they relate. There are four basic operations in the port operations block based on empirical observations at the container Port in Indonesia. The four types of operations are ship operations, quay operations, stacking yard/warehouse operations, and inland transport operations.

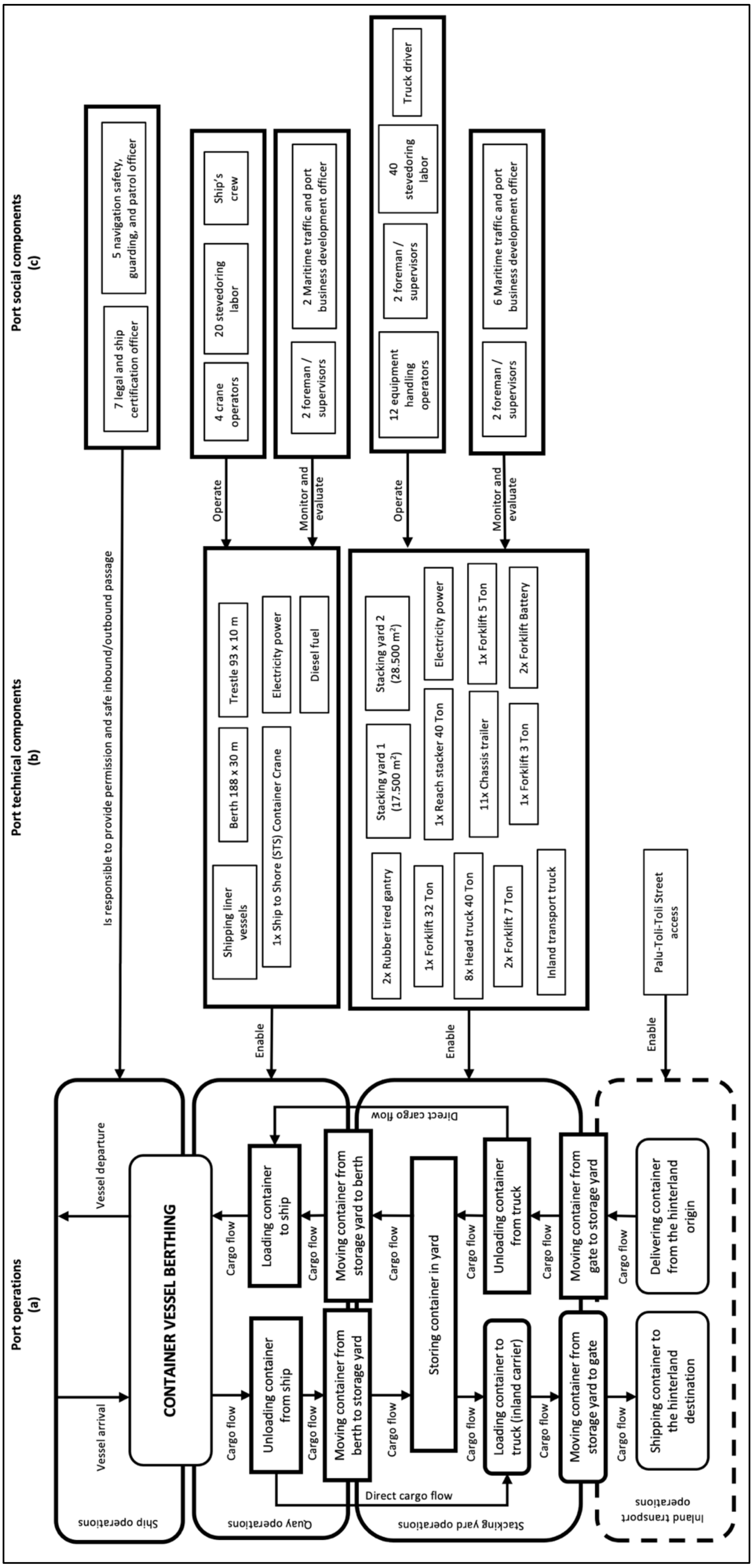


Figure 22. Block diagram of the Port of Pantoloan and its operations as a socio-technical system

The ship operations block shows the scheme of the ship's arrival, which then berths in the Port of Pantoloan and waits to be unloaded or loaded. Once the (un)loading process at the port is complete, the ship will depart from the berth. In the berthing process, port actors support the smooth operation of ship operations related to the port. KSOP officers, especially in the legal and ship certification section and the navigation safety, guarding, and patrol section, can grant permission to ships to berth at the Port of Pantoloan and ensure that the ships meet the requirements and criteria of the port law in Indonesia.

The second part is the quay operations block, where loading and unloading from and to container ships is described. The arrow in the quay operations shows the flow of cargo or containers that are being moved. The left side shows how containers move from the ship to the handling equipment and stacking yard. Additionally, containers are not always transported to be placed in the stacking yard; they can also be directly transported by inland transport for distribution to the hinterland. That's why, in the box of unloading containers from the *ship*, we also added a direct cargo transfer arrow from the ship to the inland truck. On the right side, it has the same scheme as the left side but in the opposite direction. On the right side of the quay operations, containers transported from the stacking yard by the handling equipment are moved onto the ship. In addition to containers from the stacking yard, containers transferred to the ship can also come from direct inland truck shipments that go to the quay directly.

The quay operations depend on several resources, i.e., the technical components necessary to support these operations. Additionally, on the far right in Figure 22, social components are displayed, which ensures that the facilities in the technical components can function correctly. Two types of actors are distinguished. The first actor operates these technical components, including quay crane operators and moored ship crews. In addition to operators, stevedores help load and unload cargo from and to ships manually using human labor. The other actors function as supervisors and evaluate whether the quay operation is following the applicable regulations and laws. In the Port of Pantoloan context, the officers who carry out this task are the maritime traffic officers and port business development officers from KSOP Palu Bay.

The third part of Port Operations at the Port of Pantoloan is *stacking yard operations*. The stacking yard operations focus on moving containers from and to the stacking yard. Containers taken from the ship and waiting to be moved to the hinterland (because the truck has not yet arrived) or to another port (transshipment) are temporarily stored in the stacking yard. When the actual destination ship or inland truck comes to pick up the container, the container will be moved out of the stacking yard. Meanwhile, the right side of the container flow explains that containers that have entered the port carried by the inland truck will enter the stacking yard if the ship carrying the containers has yet to arrive.

When the ship arrives, the containers in the stacking yard will be transported from the stack into the ship. Stacking yard operations do not always occur, as inland trucks can go directly to the quay to unload containers without first being stored in the stacking yard if the arrival time of the ship and the arrival of the inland truck are synchronized. To understand factors that support the smooth running of stacking yard operations, the technical components that ensure operations run smoothly are identified.

In addition, social components are also mapped to ensure that technical components can function properly. Actors who play a role in stacking yard operations are divided into field operators and supervisors. Like with the quay operations, the social components that play the role of operators are inland truck drivers and handling equipment operators. Operations in the stacking yard are also supported by manual port loading and unloading labor provided by the Stevedore Labor Cooperative. For the supervision and evaluation role, a supervisor or foreman from the terminal operator coordinates with the port authority to ensure that stacking yard operations comply with the applicable regulations.

The last operation is *inland transport operations*, which focuses on transporting containers between the Port and their origin or destination in the hinterland. The technical components section explains that the Palu-Toli-Toli road is the only access to distribute containers to their destination on the mainland. There is no other access besides the road, which means no railway and inland waterway access. The social components for inland transport are not explained in more detail because the first layer actors cannot directly intervene in the inland transport infrastructure connected to the Port of Pantoloan. Therefore, a dotted line frame is used in the Figure for the inland port operations, indicating that these operations are important in the overall port operations activity. Still, the port's first-layer actors have a limited role in these operations.

4.1.2 Analysis of Sulawesi Island's Container Ports-Hinterland Network Connectivity

This subsection presents the analysis of the ports-hinterland network connectivity for Sulawesi Island. This analysis aims to determine the quality of hinterland transport connectivity to the ports that can handle containers on Sulawesi Island. The analysis results can determine the extent of the hinterland's ability to support or be a barrier to resilience interventions when one of the container ports on Sulawesi Island is disrupted. Following the method from Chapter 3, the first thing to do is to calculate how much spare capacity is available at the alternative container ports on Sulawesi Island, SC_p, when the Port of Pantoloan is affected by the disaster. The value of SC_p for each alternative port is then converted to the "Spare Capacity Replacement Index" metric, $SCRI_p$ for which the calculation formula has been explained in Equation 3 in Chapter 3.

This study uses two data sources from the government that record how much excess capacity is available for each alternative port. The first data we use is the port masterplan document of each alternative port from the Ministry of Transportation of the Republic of Indonesia. This port masterplan contains the actual port facility conditions that existed in that period as the basis for calculating the maximum theoretical capacity of alternative ports. The second data we use is from the 2018 sea transportation statistics released by the Central Bureau of Statistics of the Republic of Indonesia, which shows the annual port capacity used.

Excess capacity for each port is then obtained by subtracting the used port capacity from the maximum theoretical capacity. Table 9 shows the SC_p and $SCRI_p$ calculation results for each port on Sulawesi Island concerning the needs of the Port of Pantoloan when it temporarily shuts down due to a disaster. In this case, we've determined that the minimum daily capacity needed by the Port of Pantoloan, SC_d, is approximately 825 TEUs, obtained from the total capacity of the container ships serviced by the Port of Pantoloan divided by the number of days in 6 months between April – September 2018. SC_d is used as the denominator to convert SC_p into $SCRI_p$.

The data indicates that the container port of Makassar possesses the highest $SCRI_p$, which suggests that it can support the entirety of the capacity lost by the Port of Pantoloan, almost doubling it. However, the effective amount needed is only 100%, as the focus is on capturing the daily capacity needed by the Port of Pantoloan. In addition to the Port of Makassar, the combined total $SCRI_p$ from three ports, namely Kendari, Bitung, and Gorontalo, can also compensate for 100% of Pantoloan Port's lost capacity due to natural disasters. However, these three ports are located in the central and northern parts of Sulawesi Island and are scattered and far from each other.

Table 9. The SC_p and $SCRI_p$ value of ports in Sulawesi to replace the lost capacity from the Port of Pantoloan

Container ports in Sulawesi	**Daily Spare Capacity in TEUs (SC_p)**	**Spare capacity replacement per port ($SCRI_p$)**
Makassar	1466	178%
Kendari	377	46%
Bitung	311	38%
Gorontalo	139	17%
Luwuk	27	3%
Toli-Toli	16	2%
Anggrek	15	2%
Malili	9	1%
Pare-Pare	7	1%

At the next stage, we use the metrics "the *number of inland transport resources required per day to utilize the spare capacity of alternative ports at the given period of t*", or $N_p(t)$ as shown in Equation (4) to analyze how accessible the Port of Pantoloan is from alternative container ports in Sulawesi Island. This $N_p(t)$ value will be useful compared to how many inland transport vehicles are available on the island. A large gap between the availability of inland transport on the island and the value of $N_p(t)$ indicates that the Port of Pantoloan will be more difficult to access from other ports in Sulawesi Island. In the case study at the Port of Pantoloan, the only inland transport mode considered is container trucks with a capacity of 1 TEU. Container trucks with a capacity of 1 TEU are the main inland transport mode between ports in Sulawesi Island because many roads are still not passable by trucks with a capacity of 2 TEUs or more.

To calculate $N_p(t)$, we need the value of dt_p which is the shortest time spent on a round trip from alternative port p to disrupted port d. To determine the value of dt_p, we identify all roads that can be traveled by a container truck with a capacity of 1 TEU. We used data from the Indonesian National Geospatial Information Agency (*Badan Informasi Geospasial*/BIG) to find the roads that connect the ports and can be traveled by container trucks with a capacity of 1 TEU. As outlined in Table 10, these roads bridge the Port of Pantoloan to other container ports in Sulawesi, and the table details road names, terrain types, distances (in kilometers), and average travel durations (in minutes). Figure 23 illustrates the spatial distribution of all container ports on Sulawesi Island, listed in Table 9, and the road network is described in Table 10.

Regarding terrain, Sulawesi's hinterland can be categorized into two main types. The first type consists of flat roads predominantly found along the coastlines, such as the Toli-Toli - Palu road and the Majene - Mamuju Axis road. In contrast, the second type encompasses roads that traverse hilly and mountainous areas. A main example is the Trans Sulawesi Highway, a primary channel connecting various provinces across Sulawesi Island. This distinction between flat and mountainous roads directly impacts the vehicular speed of trucks. Typically, vehicles in a mountainous terrain move slower than those in a flat terrain. Even when mountainous roads are shorter in distance, their travel times can often exceed those of flat roads.

Table 10. List of roads connecting the Port of Pantoloan to other container ports on Sulawesi Island

Origin - Destination	**Name**	**Terrain / Type**	**Distance (km)**	**Average one-way Travel Time (Min), dt_p**
Toli-Toli - Pantoloan	Jl. Toli-Toli - Palu (Route 1)	Coastal flat road	406	570
Toli-Toli - Pantoloan	Jl. Trans Sulawesi (Route 2)	Mountain road	366	519
Anggrek - Pantoloan	Jl. Trans Sulawesi	Mountain road	574	742
Bitung - Pantoloan	Jl. Trans Sulawesi	Mountain road	976	1,297
Gorontalo - Pantoloan	Jl. Trans Sulawesi	Mountain road	592	764
Luwuk - Pantoloan	Jl. Trans Sulawesi	Mountain road	577	745
Kendari - Pantoloan	Jl. Trans Sulawesi	Mountain road	808	1,139
Bau-Bau - Pantoloan	-		-	-
Malili - Pantoloan	Jl. Trans Sulawesi	Mountain road	463	660
Makassar - Pantoloan	Jl. Poros Majene - Mamuju (Route 1)	Coastal flat road	845	1,139
Makassar - Pantoloan	Jl. Trans Sulawesi (Route 2)	Mountain road	921	1,279
Pare-Pare - Pantoloan	Jl. Poros Majene-Mamuju (Route 1)	Coastal flat road	693	977
Pare-Pare - Pantoloan	Jl. Trans Sulawesi (Route 2)	Mountain road	771	1,109

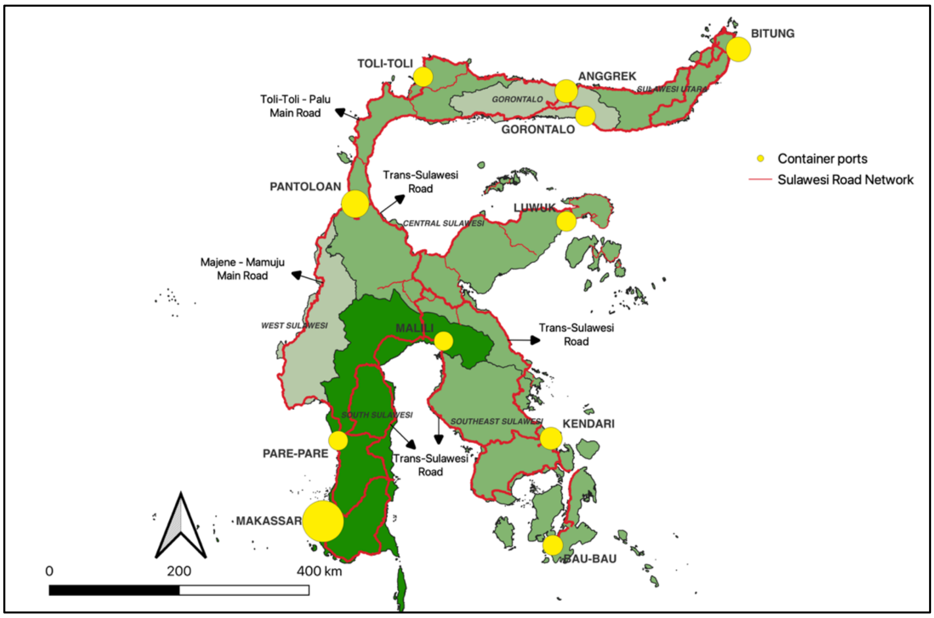


Figure 23. The road network (hinterland) that connects the Port of Pantoloan with other container ports on Sulawesi Island

The value of dt_p can be calculated after listing all road sections connecting all container ports on Sulawesi Island, including the Port of Pantoloan. The value of dt_p that will be used to calculate the value of $N_p(t)$ is the lowest value, or min dt_p. This min dt_p value is taken from the lowest average one-way travel time from various alternative road sections connecting a pair of ports. For example, the Port of Toli-Toli - Pantoloan O-D pair has two alternative road segments with dt_p values of 570 and 519 minutes, respectively. To calculate $N_p(t)$, the value of 519 is used as min dt_p as described in Equation 4. Table 11 presents the calculation of $N_p(t)$ for each port on Sulawesi Island.

Table 11. Number of trucks needed to capture the port spare capacity per day

Port	**Daily Available spare capacity (TEU) Daily (SC_p)**	**Average Round trip travel time in Hour (dt_p)**	**Number of trucks (1 TEU) needed to capture the port spare capacity per day ($N_p(t)$)**
Makassar	842*	43.2	1,517
Kendari	377	38.0	597
Bitung	311	24.7	321
Gorontalo	139	25.5	148
Luwuk	27	24.8	28
Toli-Toli	16	17.3	11
Anggrek	15	24.7	15
Malili	9	22.0	8
Pare-Pare	7	32.6	10

*) The asterisk indicates an adjustment to the spare capacity at the Port of Makassar, which the Port of Pantoloan can utilize during a disaster, where it represents 100% of the lost capacity.

Based on the calculations shown in Table 11, it can be seen that 1,517 trucks, each with a capacity of 1 TEU, are required to compensate for the demand lost of the Port of Pantoloan in the event of a disaster. This assumes that the Port of Makassar is the sole port to provide its spare capacity to the Port of Pantoloan. Alternatively, if the Port of Makassar is also unavailable to provide its spare capacity, the Port of Pantoloan can turn to the Ports of Kendari, Bitung, and Gorontalo to recapture its demand. Interestingly, utilizing these three ports can reduce the number of trucks needed by 30% compared to solely relying on the Port of Makassar. Using these three ports' spare capacity makes it possible to reduce the resource gap to fulfill the demand for the Port of Pantoloan when it is disrupted. However, the different spatial locations and management of the alternative ports will require coordinating the utilization of spare capacity, which is more complex than only utilizing the spare capacity at one port, such as the Port of Makassar.

Based on the empirical findings, we can infer that the ports-hinterland network in Sulawesi Island provides multiple options to replace operational capacity if the Port of Pantoloan is disrupted. The first option is to use the spare capacity available at the Port of Makassar, located in the southern part of Sulawesi Island. Makassar Container Port is the port with the largest capacity on Sulawesi Island and is theoretically capable of replacing the capacity of the Port of Pantoloan when disrupted. However, its relatively far distance from the Port of Pantoloan makes the inland transport resources required to use this spare capacity higher. Another option is to use spare capacity from three ports, namely Kendari, Bitung, and Gorontalo Ports, which accumulatively can replace the capacity of the disrupted Port of Pantoloan. The amount of inland transport resources required is relatively less than the spare capacity at the Port of Makassar because the three ports are closer to the Port of Pantoloan. The fundamental challenge in utilizing the spare capacity is coordinating with stakeholders from multiple ports, which is relatively more complex than coordinating with a single port.

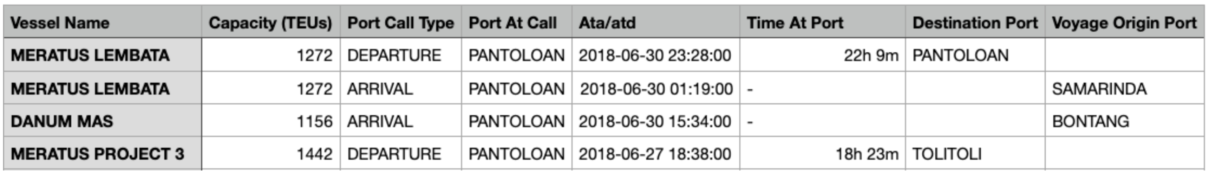
4.1.3 Analysis of Sulawesi Island's Container Shipping Connectivity

In this section, the level of connectivity of Sulawesi Island in terms of container ship traffic is analyzed. The results of the analysis can provide an understanding of how each port on Sulawesi Island contributes to shipping connectivity and the level of isolation on Sulawesi Island. For this analysis, we use graph theory using Equation 1 from Chapter 3 of this thesis, to calculate the connectivity of each port that can handle containers on Sulawesi Island. The connectivity value of individual port i is derived from the product of the maximum theoretical container vessel capacity (TEUs) that visits port i and the frequency of vessel visits within a specific time frame. Furthermore, to calculate the connectivity level of Sulawesi Island, Equation 2 in Chapter 3 is used. Using Equation 2, the connectivity level of Sulawesi Island is the sum of the total connectivity of all ports that can handle containers on the island.

Based on data we received from the Republic of Indonesia's Sea Transportation Statistics in 2018 (BPS, 2019), we found that 104 seaports are operating on Sulawesi Island. Of these 104 ports, nine are commercial, and 95 are non-commercial ports. Based on the port call data we received from AIS and internal data from the Ministry of Transportation of the Republic of Indonesia (especially for small ports), we found that there are only 11 ports that handle container flows regularly. We will use these 11 ports to calculate the container shipping connectivity of Sulawesi Island.

To calculate the connectivity level of each port regarding container vessels, we used data obtained from a third-party Automatic Identification System (AIS) service. The reason we used AIS is that the AIS service covers the port call data of the eleven ports. In addition, the data from AIS provides an accurate representation of the traffic flow, which is very difficult to obtain, especially from commercial Ports in Indonesia. The small subset of the container vessel traffic dataset from AIS entering and exiting the Port of Pantoloan, one of the 11 container-handling ports on Sulawesi Island, is presented in Table 12. This dataset comprises the following elements: Vessel Name, Capacity (TEUs), Port Call Type, Actual Time of Arrival (ATA) or Actual Time of Departure (ATD), Time At Port, Destination Port, and Voyage Origin Port. Using the datasets shown in Table 12, we calculated the connectivity of container shipping from each port on Sulawesi Island. The dataset for calculating connectivity covers six months (180) days before the disaster at the Port of Pantoloan, specifically from April 1 to September 27, 2018. A total of 43,500 vessel entries in the dataset during that period were then analyzed.

Table 12. An illustration of the dataset header used for calculating Sulawesi Island's container shipping connectivity



Vessel Name	Capacity (TEUs)	Port Call Type	Port At Call	Ata/atd	Time At Port	Destination Port	Voyage Origin Port
MERATUS LEMBATA	1272	DEPARTURE	PANTOLOAN	2018-06-30 23:28:00	22h 9m	PANTOLOAN	
MERATUS LEMBATA	1272	ARRIVAL	PANTOLOAN	2018-06-30 01:19:00	-		SAMARINDA
DANUM MAS	1156	ARRIVAL	PANTOLOAN	2018-06-30 15:34:00	-		BONTANG
MERATUS PROJECT 3	1442	DEPARTURE	PANTOLOAN	2018-06-27 18:38:00	18h 23m	TOLITOLI	

The calculation results of container shipping connectivity at each port are shown in Table 13. In the table, the calculation results using Equation (1) are ranked from the highest average connectivity to the lowest. Based on the results of empirical calculations, it is known that the Port of Makassar has the largest level of connectivity, followed by the Port of Pantoloan as the port with the second largest level of container shipping connectivity. At the end of the table, we obtained the container shipping connectivity level of Sulawesi Island by adding all connectivity levels of each port. In normal conditions, we found that Sulawesi Island's connectivity for container shipping services is 836,073 TEUs in 6 months, or 4,645 TEUs daily.

Table 13. Container port connectivity for Sulawesi Island in 2018

Rank	**Port**	**The port's shipping connectivity for 6 months (in TEUs)**	**Average port's shipping connectivity per day (in TEUs)**
1	Makassar	380,859	2,116
2	Pantoloan	148,420	825
3	Bitung	94,019	522
4	Anggrek	70,327	391
5	Kendari	57,092	317
6	Bau-Bau/Murhum	21,547	120
7	Luwuk	20,189	112
8	Gorontalo	19,979	111
9	Toli-Toli	15,135	84
10	Pare-Pare	4,666	26
11	Malili	3,840	21
Sulawesi Island's connectivity		**836,073**	**4,645**

Figure 24 shows the spatial distribution of the container ports on Sulawesi Island. In the figure, the yellow circles are ports that can handle container flows. The size of the yellow circle indicates the connectivity level of the port. The larger the size, the greater the level of shipping connectivity. The three ports that have the highest connectivity are spatially distributed. The Port of Makassar, the port with the highest connectivity, is located in South Sulawesi, the province with the highest population density in the region. Meanwhile, the Port of Pantoloan is in Central Sulawesi, and the Port of Bitung is in North Sulawesi, which has a medium population density.

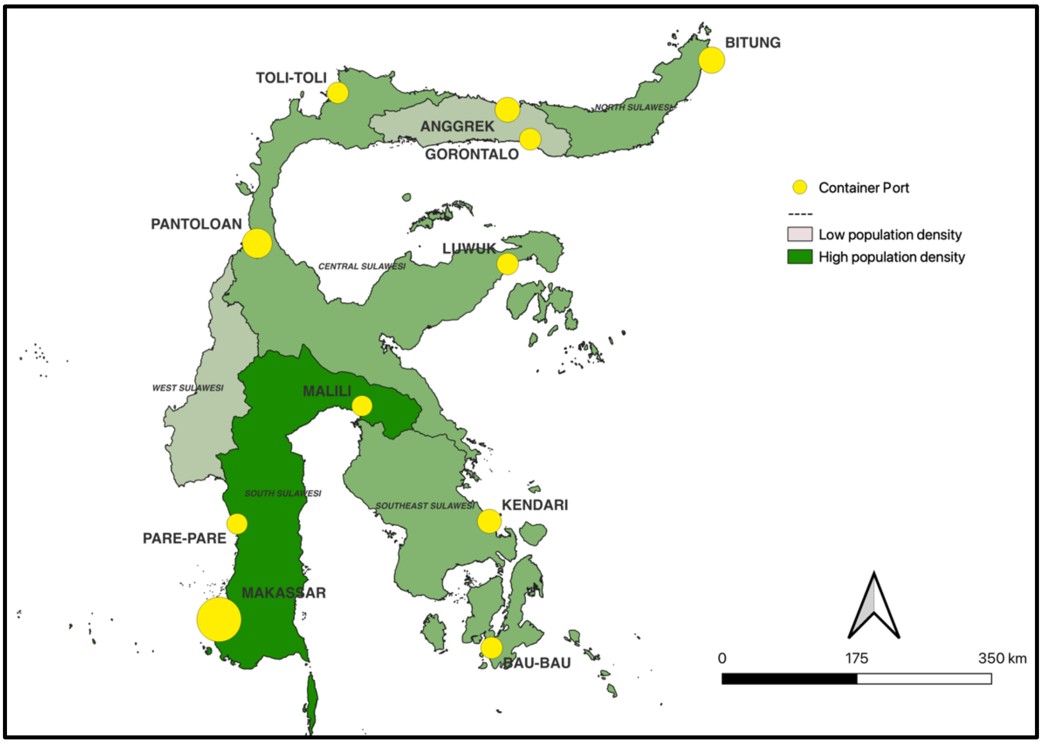


Figure 24. Spatial distribution and connectivity of container ports in Sulawesi Island

The AIS dataset from 1 April to 27 September 2018 was also used to analyze shipping services directly related to the Port of Pantoloan. This analysis aims to determine the origin and destination (inbound and outbound) of goods shipped to and from the Port of Pantoloan. This analysis only includes direct shipping services. The results of this analysis can later be used as a benchmark to determine how the shipping service connected to the Port of Pantoloan changed after the disaster. Table 14 presents a list of origin-destination pairs of ports that have container shipping services linked to the Port of Pantoloan, including the container shipping capacity in TEUs.

Table 14. List of container shipping legs that directly connected to Port of Pantoloan in 2018 (Pre-disaster)

Inbound Link	Container shipping capacity (TEUs)	Outbound Link	Container shipping capacity (TEUs)
Ambon - Pantoloan	20,853	Pantoloan - Toli-Toli	23,878
Semarang/Tanjung Emas - Pantoloan	17,815	Pantoloan - Tenau/Kupang	19,830
Tarakan - Pantoloan	14,186	Pantoloan - Bitung	17,514
Kuala Tanjung - Pantoloan	12,661	Pantoloan - Banjarmasin	12,674
Tenau/Kupang - Pantoloan	11,825	Pantoloan - Belawan	11,752
Wini - Pantoloan	11,482	Pantoloan - Tanjung Perak	11,268
Tanjung Perak - Pantoloan	11,454	Pantoloan - Tarakan	9,845
Anggrek - Pantoloan	10,863	Pantoloan - Ambon	9,179
Nunukan - Pantoloan	9,767	Pantoloan - Samarinda	8,377
Toli-Toli - Pantoloan	9,685	Pantoloan - Wini	8,359
Banjarmasin - Pantoloan	8,987	Pantoloan - Maumere	7,934
Samarinda - Pantoloan	8,842	Pantoloan - Tanjung Priok	7,808
Total	**148,420**		**148,420**

The spatial distribution of inbound edges of the Port of Pantoloan is illustrated in Figure 25. In this figure, the size of the vertices at each port represents the total national capacity of container shipping service capacity connected to that port. The thickness of the red line on the edges shows the inbound container shipping capacity from a domestic port to the Port of Pantoloan. The empirical analysis shows four ports have the largest capacity for sending container shipments to the Port of Pantoloan: the Ports of Ambon, Semarang, Tarakan, and Kuala Tanjung. This indicates that the containers arriving at the Port of Pantoloan originate outside Sulawesi Island, particularly from the Maluku Islands, Java, Kalimantan, and Sumatra Island. A small container shipping service capacity comes from Sulawesi Island and the East Nusa Tenggara region.

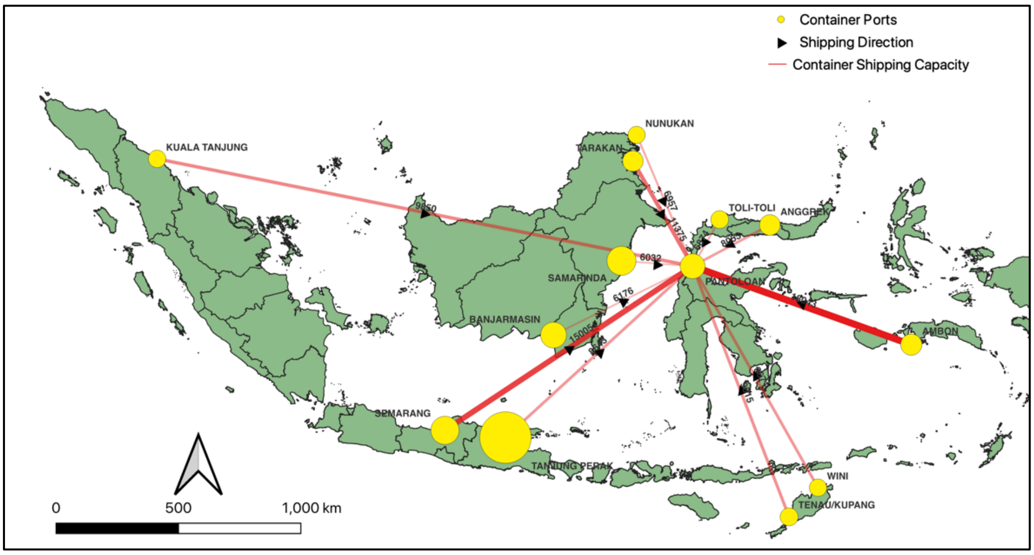


Figure 25. Inbound links of container shipping services connected to the Port of Pantoloan in 2018 before the disaster

The outbound capacity of container shipping services connected to the Port of Pantoloan is depicted in Figure 26. Based on the data analysis, Toli-Toli, Tenau/Kupang, Bitung, and Banjarmasin ports have the largest capacity for shipping containers from the Port of Pantoloan. This indicates that cargo shipped from the Port of Pantoloan aims to fulfill demand within and around Sulawesi Island, such as Kalimantan Island and the East Nusa Tenggara region. Long-distance shipments to other islands only have a small shipping capacity.

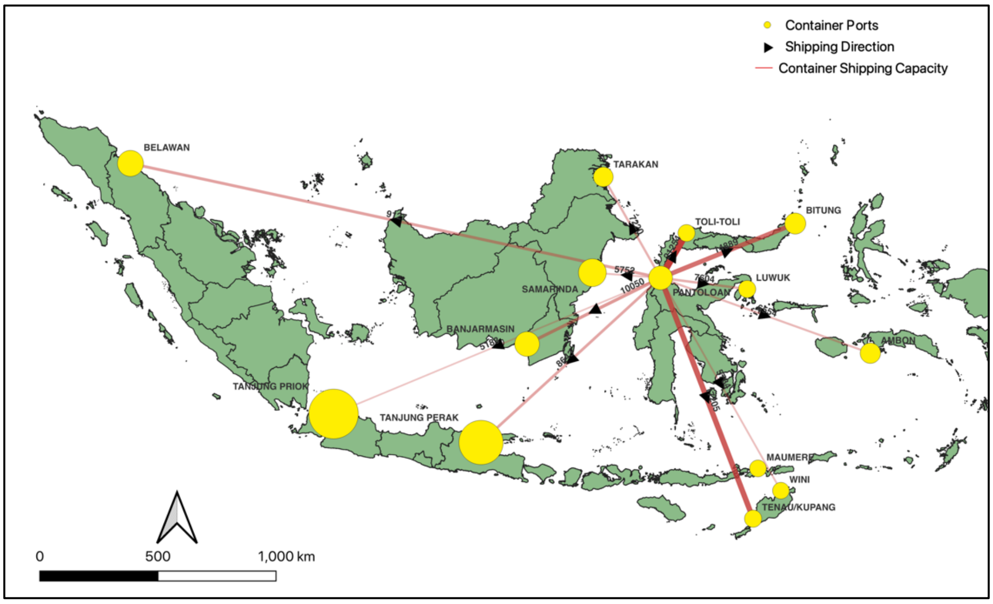


Figure 26. Outbound links of container shipping service connected from the Port of Pantoloan in 2018 before the disaster

4.2 Phase 2: Resilience curve analysis

This subsection will discuss how the earthquake affected operations at the Port of Pantoloan over time using the resilience curve explained in Chapter 2. A detailed explanation of the resilience curve can be found in sub-section 2.5 in Chapter 2. To build the resilience curve, it is necessary to select the primary indicators to measure the Port of Pantoloan's operational performance changes after a disaster. In this case study, the selected performance indicator is related to the productivity of the Port of Pantoloan in serving container ships in Indonesia, following its main purpose as a commercial port.

The main metric we use to measure productivity is Container Vessel Capacity (CVC). CVC is a metric to measure how much of the theoretical maximum capacity of vessels that the Port of Pantoloan serves in a certain period. For example, suppose the Port of Pantoloan serves two vessels in one day, such as Meratus Lembata and Danum Mas, which have a theoretical maximum capacity of 1,272 and 1,156 TEUs, respectively. In that case, the CVC on that day is 2,428 TEUs. The reason for choosing this metric instead of the fraction or percentage of actual capacity used is to make it easier to estimate how much alternative port backup capacity on the same island is needed if Pantoloan port is operationally disrupted.

The selection of CVC as the main metric has been validated by the experts listed in Table 8 because it can directly indicate the productivity of the Port of Pantoloan in handling the flow of container ships in Indonesia. In addition, the use of CVC as a metric can be used as a solution to the difficulty of obtaining the actual daily container loading and unloading data because it is categorized as highly confidential data of shipping companies and port management that is not made available to the general public.

We used data from two empirical sources, AIS and INAPORTNET, to develop the resilience curve. As a main container port on Sulawesi Island, the Port of Pantoloan is covered by AIS and INAPORTNET services. We used both to ensure that the resilience curve plotted has high data accuracy and high data completeness. The AIS and INAPORTNET data we use is a dataset of ships entering and exiting the Port of Pantoloan from April 1, 2018, to August 1, 2019. The dataset we analyzed contains only commercial container ships and does not include humanitarian ships that bring humanitarian assistance to victims of natural disasters.

The AIS dataset has precise timestamp details of ship arrivals and departures. However, not all ships (especially small and medium-sized commercial ships owned by local Indonesian businesses) are included in the AIS data. While the data in INAPORTNET does not have the same level of accuracy for the timestamps of arrival and departure as the AIS, the coverage of commercial vessels visiting and leaving the Port of Pantoloan is more complete as it does not only contain large vessels but also small and medium-sized private vessels that are not included in the AIS. Using these two data sources, we created a combined dataset to plot the resilience curve for this case study. We then processed the dataset and plotted the behavior over time of CVC using 3-day average smoothing from Equation (5) in Chapter 3 from August 2018 to August 2019.

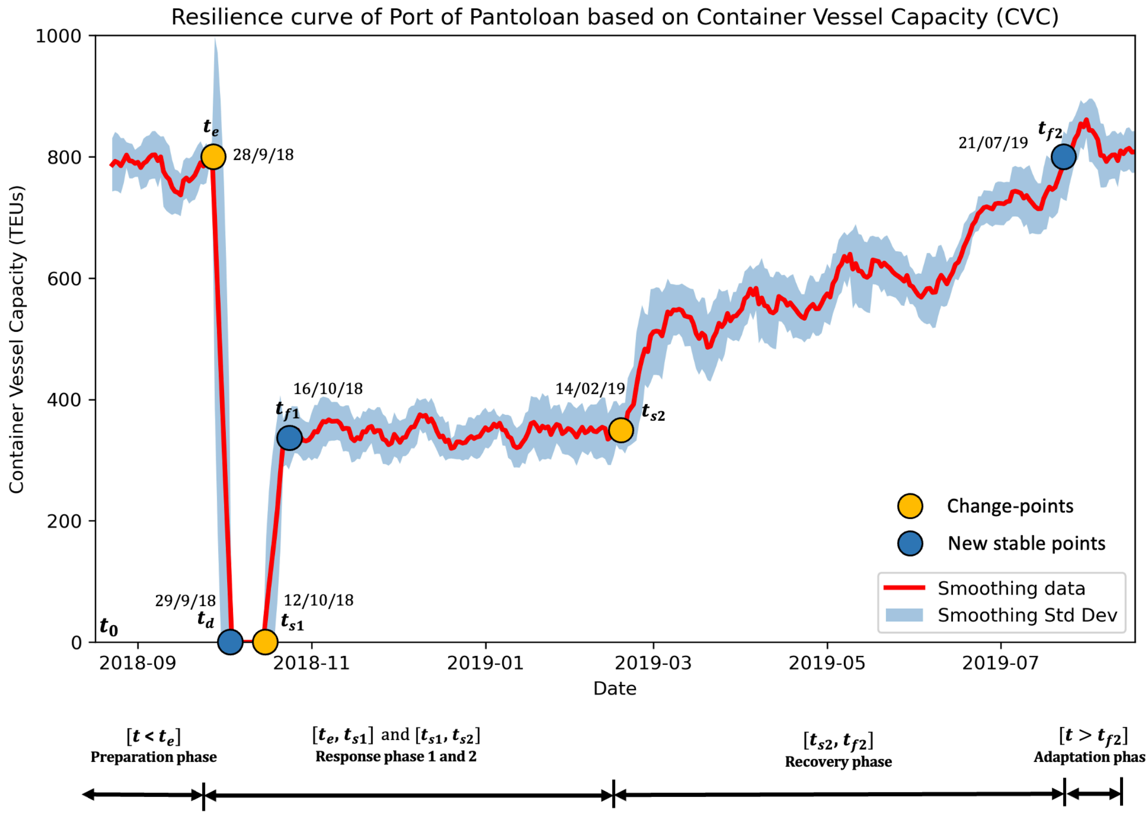


Figure 27. The empirical resilience curve of the Port of Pantoloan presented in a 3-day average

Figure 27 shows a graph of the CVC behavior over time. From this behavior, we identified six important points in the curve. The procedure for determining these points and what they mean is explained in more detail in Section 3.2.2 of Chapter 3. These points are useful in determining the phases of the resilience cycle, such as the preparation, response, recovery, and adaptation phases. Details of these six points, including when they occurred and specific descriptions of what events occurred at the time, are provided in Table 15.

Table 15. A table detailing six critical points of time in the empirical resilience curve of the Port of Pantoloan

Point symbol	Type	Date	Events
t_e	Changepoint	September 28, 2018	An earthquake and tsunami measuring 7.5 Mw struck the Port of Pantoloan
t_d	New stable point	September 29, 2018	PT. Pelindo IV and the Port Authority announced the temporary closure of the Port of Pantoloan for commercial container ship services.
t_{s1}	Changepoint	October 12, 2018	Port operator PT. Pelindo IV announced the reopening of the Port of Pantoloan to serve commercial container ships.
t_{f1}	New stable point	October 16, 2018	Ship traffic at the Port of Pantoloan increased and experienced heavy congestion because the Port reached its maximum capacity. The Port also handled additional ship traffic from small ports around the Port of Pantoloan that were affected, namely the Port of Donggala and the Port of Wani.
t_{s2}	Changepoint	February 14, 2019	The loading and unloading capacity of the Port of Pantoloan returned to normal because the collapsed quay crane affected by the disaster has been successfully replaced with a new quay crane.
t_{f2}	New stable point	July 21, 2019	The traffic flow at Pantoloan Port returned to what it was before the earthquake and tsunami.

After completing the resilience curve and identifying six critical points in time, we validated the curve with experts (via email due to the COVID-19 pandemic). The experts we asked were KSOP officers in the Marine Safety, Guard, and Patrol section who were directly involved in handling and recovering the Port of Pantoloan after being affected by the earthquake and tsunami. The results of the resilience curve development in Figure 27 and the identification of the six points shown in Table 15 have been declared valid following the real-world incident. This expert-validated resilience curve is then used to calculate the Port's resilience attributes. Five resilience attributes can be derived using metrics based on performance, time, or a combination of both (See Table 3). The results of the resilience attributes calculation can be seen in Table 16.

Table 16. Assessment of the resilience attributes of the Port of Pantoloan, along with its reasoning based on the validated resilience curve

Resilience attribute	Metrics and theoretical formula	Empirical value	Reasoning
Robustness	Average residual performance from t_d to t_s , $f(t_d)$/day	0 TEUs/day	After being hit by an earthquake and tsunami, the performance of incoming commercial ships dropped to 0 TEUs per day. The ability to withstand the disaster can also be measured by the attribute "Vulnerability," which is the inverse of "Robustness." Based on the Vulnerability attribute, the total loss (*depth of impact*) experienced by the Port of Pantoloan was an incoming ship traffic of 834 TEUs per day.
Vulnerability	Average depth of performance decline from t_d to t_s, $f(t_0) - f(t_d)$/day	834 TEUs/day	
Responsiveness (Phase 1)	Duration of time spent at response phase 1 $(t_{s1} - t_d)$	14 days	The first response phase was taken after the earthquake and tsunami, when the Port Authority and Pantoloan Port announced to close all services for commercial vessels on September 29, 2018, until it was decided to reopen with limited capacity on October 12, 2018, for a total duration of 14 days.
Responsiveness (Phase 2)	Duration of time spent at response phase 2 $(t_{s2} - t_{s1})$	125 days	The second response phase of the port began when it officially reopened for commercial ships on October 12, 2018, and continued until the port regained its full cargo handling capacity on February 14, 2019, spanning a total duration of 125 days.
Rapidity	Duration of time spent at recovery $(t_{f2} - t_{s2})$	157 days	This period started on February 15, when the Port of Pantoloan returned to its original capacity, and continued until July 21, 2019. On this day, for the first time, the total capacity of container ships visiting the Port of Pantoloan reached the performance seen before the earthquake and tsunamis struck the port.
Recoverability	Speed of recovery, $\frac{df(t_{s2})}{dt}$	3 TEUs / day	The recoverability value is derived from the difference between the average residual performance from $[t_{f1}, t_{s2}]$ and the average performance value before the disaster, divided by the required recovery duration. Thus, from the calculation (834 - 346) TEUs / 157 days, we obtain a recovery speed (recoverability) of 3 TEUs / day.

In summary, in phase 2, the resilience curve analysis was implemented for the Port of Pantoloan, which was affected by the earthquake and tsunami on September 28, 2018. The indicator used to measure port performance is productivity, with the Container Vessel Capacity (CVC) metric as the basis for the resilience curve. The results of this phase 2 analysis can be a reference for ports with characteristics similar to the Port of Pantoloan (See section 4.1) and in areas with the potential for earthquake and tsunami disasters of high magnitude. The properties that can be used are the behavior of the CVC over time and the values of the resilience attributes calculated based on the validated resilience curve.

Based on empirical findings from the analysis conducted in phase 2, it was found that the CVC behavior change curve of Pantoloan Port has a multi-staging response phase. The multi-staging response phase in the resilience curve shows an effort to restore CVC as soon as possible, even though the port's loading and unloading capacity has not fully returned (partial function). While the port runs at partial capacity, the second response phase focuses on preparing to recover port performance to an acceptable or pre-disaster performance level. Our findings slightly differ from most theoretical resilience curves in the context of ports that only have a single-stage response and immediately focus on recovering performance levels to pre-disaster levels.

In addition to knowing the behavior of the performance indicators of interest over time, the resilience curve validated by experts or stakeholders can also be used to calculate resilience attributes. These resilience attributes are the components that define the overall resilience of the Port of Pantoloan. Resilience attributes such as *robustness* or *vulnerability* can be used to determine how strong Pantoloan Port is in resisting damage from earthquakes and tsunamis. The robustness and vulnerability values of the Port of Pantoloan are 0 TEU/day and 834 TEUs/day. Looking at these resilience attributes, we can see that the Port of Pantoloan is very vulnerable to large-scale earthquake and tsunami disasters.

Meanwhile, the resilience attribute responsiveness can be used to determine how agile the Port of Pantoloan is in preparing resources to start port performance recovery. It was recorded that the total responsiveness time spent preparing for the Port CVC recovery process was 139 days. This total time shows the efforts of stakeholders at the Port of Pantoloan in initiating cooperation, obtaining the resources needed, and formulating what strategies can be used to start recovering port performance.

When the resources needed to restore port performance to pre-disaster conditions are fulfilled, *rapidity* or *recoverability* can measure how quickly port performance returns from disrupted conditions to a pre-disaster state. A rapidity value of 157 days was recorded. This time shows how long the Port of Pantoloan's loading and unloading capacity takes to return to the pre-disaster state. Another attribute *recoverability* shows 3 TEUs / day, indicating the average speed of how many CVCs can be recovered per day by the Port of Pantoloan after the disaster.

4.3 Phase 3: Disaster impact analysis

Section 4.3 shows the third phase of the empirical analysis of the port resilience method: the disaster impact analysis. This phase aims to determine the impacts of the disruption on the port, port-hinterland network, and island's shipping network connectivity. The analysis in this phase is divided into three sections. Subsection 4.3.1 will focus on the direct impacts experienced by the Port of Pantoloan during the September 2018 earthquake and tsunami. Subsection 4.3.2 discusses how the natural disaster directly impacted the ports-hinterland network on Sulawesi Island and whether there was any indirect impact on the Port of Pantoloan's operations. Finally, subsection 4.3.3 discusses the indirect impact of the disaster on the island's shipping connectivity. In this last subsection, the analysis emphasizes the changes in the island's shipping connectivity after the disruption of the port. In other words, this subsection shows the ripple effect when the Port of Pantoloan was affected by the disaster, especially related to maritime shipping connectivity.

4.3.1 Disaster impact analysis in the Port of Pantoloan's Socio-Technical Components

This subsection will explain how the earthquake and tsunami event in Central Sulawesi on September 28, 2018, affected the operations of the Port of Pantoloan. Specifically, this subsection will discuss the operational conditions of the Port of Pantoloan and its technical and social components at point t_d on the resilience curve in Figure 27. To determine these conditions, we processed secondary data from two field survey reports from the Government, three field survey reports from independent research consortiums, nine scientific articles, and 17 press archives (See the list of documents at the end of this chapter for more details from [4-1] to [4-31]).

The port components shown in the block diagram in phase 1, as given in Figure 22, are used again as a list of technical and social components checked for post-disaster conditions. The PIDA[13] sheet shown in Figure 13 is the main tool used to display the results of the qualitative codification of the reports. The impact analysis results are then displayed in the form of PIDA sheets. The following briefly explains the components at the Port of Pantoloan that were affected by the earthquake and tsunami in September 2018.

For the technical component, the focus of analysis in this phase is on quay and yard operations, as shown in Figure 28. These two types of operations were chosen because they are port operational areas under the authority of the KSOP Class II Palu Bay and Port Operators. Three components were declared heavily damaged in the quay operations section, so they could not be used: the berth, the container quay crane, and the electricity or power supply. For berth, the tsunami caused a lot of building debris that was scattered along the berth and hindered berthing ships at the Port of Pantoloan.

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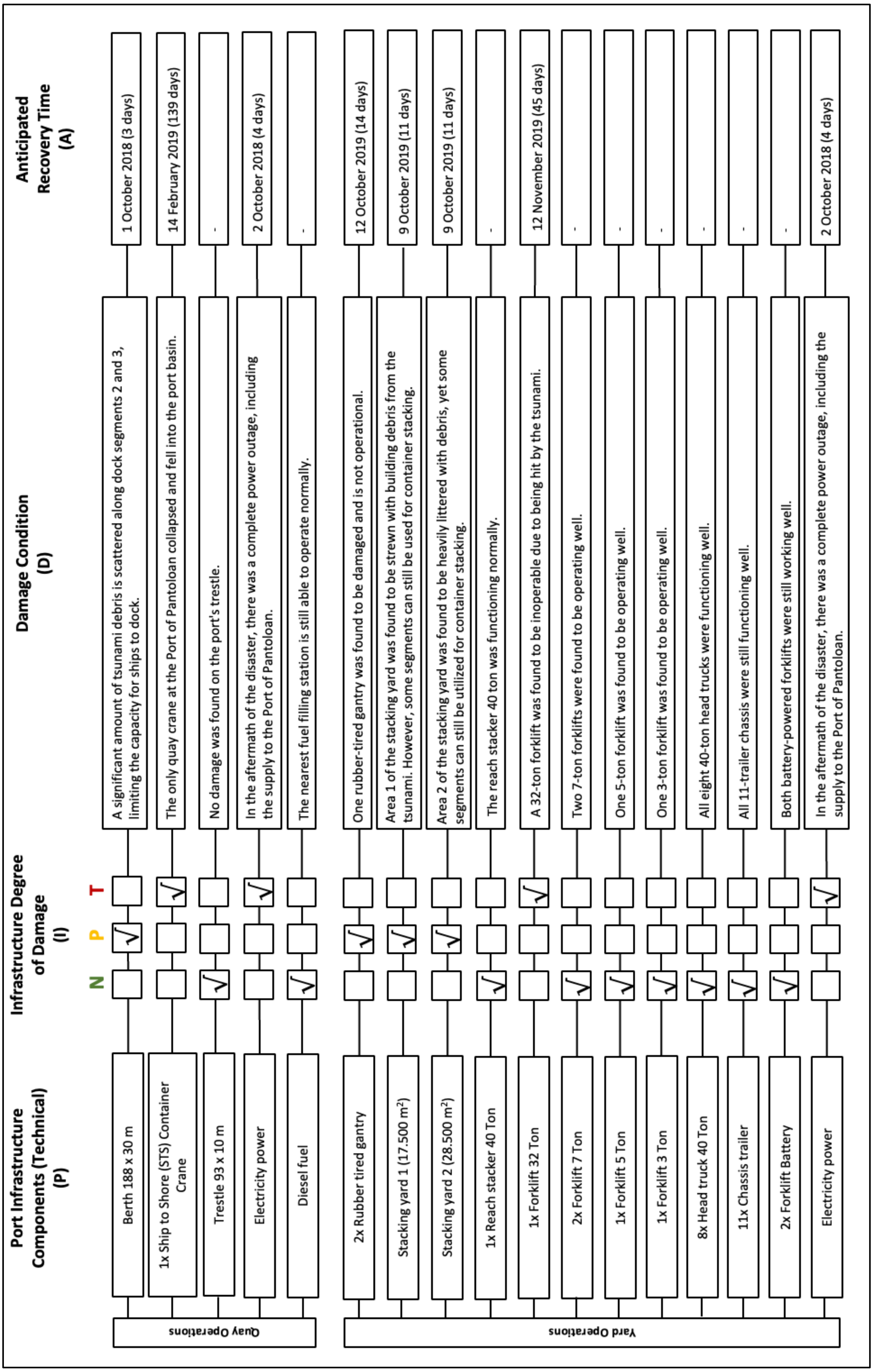
[13] PIDA stands for Port Infrastructure Damage Assessment, a tool proposed to recap the assessment of damage sustained by ports due to natural disasters or other disruptive factors. More details about PIDA are explained in section 3.2.3.

In addition, there was also a stranded passenger vessel at one of the berth segments, which caused the berth to be unusable for berthing, as shown in Figure 29a. The quay crane (ship-to-shore container crane) at the Port of Pantoloan collapsed into the side of the harbor pool so ships could not dock, disrupting the container loading and unloading process, as shown in Figure 29b. The function of the collapsed quay crane was restored on February 14, 2019, 139 days after the earthquake and tsunami hit the Port of Pantoloan. In addition, many damaged electrical installations on the mainland cut the electricity flow to supply the Port of Pantoloan operations. This power outage at the Port of Pantoloan lasted 4 days until October 2, 2018.

Related to the stacking yard's operations, two categories of impacts occurred for the technical components of the Port of Pantoloan. The first category is partially damaged components, namely stacking yards and rubber-tired gantry (RTG) cranes. The stacking yard is categorized as partially affected as the empty land not filled with containers was filled with building debris and garbage deposited by the tsunami (Figure 30a). In contrast, several areas of the stacking yard were unaffected and could be used to store containers (Figure 30b). The infrastructure of the stacking yard itself was not damaged. It took 11 days to clean up the affected stacking yard so that the entire area could be reused as before. The second category is totally damaged components, namely handling equipment in the form of a 32-ton forklift, which could not be operated because tsunami waves hit it. A replacement for this forklift arrived and was ready for operation at the Port of Pantoloan 45 days after the disaster. The other component that was totally affected was the electricity supply, which was completely shut down for 4 days because the main electricity generators on the hinterland were affected by the tsunami.



	Port Infrastructure Components (Technical) (P)	Infrastructure Degree of Damage (I) N	P	T	Damage Condition (D)	Anticipated Recovery Time (A)
Quay Operations	Berth 188 x 30 m	☐	✓	☐	A significant amount of tsunami debris is scattered along dock segments 2 and 3, limiting the capacity for ships to dock.	1 October 2018 (3 days)
	1x Ship to Shore (STS) Container Crane	☐	☐	✓	The only quay crane at the Port of Pantoloan collapsed and fell into the port basin.	14 February 2019 (139 days)
	Trestle 93 x 10 m	✓	☐	☐	No damage was found on the port's trestle.	-
	Electricity power	☐	☐	✓	In the aftermath of the disaster, there was a complete power outage, including the supply to the Port of Pantoloan.	2 October 2018 (4 days)
	Diesel fuel	✓	☐	☐	The nearest fuel filling station is still able to operate normally.	-
Yard Operations	2x Rubber tired gantry	☐	✓	☐	One rubber-tired gantry was found to be damaged and is not operational.	12 October 2019 (14 days)
	Stacking yard 1 (17.500 m^2)	☐	✓	☐	Area 1 of the stacking yard was found to be strewn with building debris from the tsunami. However, some segments can still be used for container stacking.	9 October 2019 (11 days)
	Stacking yard 2 (28.500 m^2)	☐	✓	☐	Area 2 of the stacking yard was found to be heavily littered with debris, yet some segments can still be utilized for container stacking.	9 October 2019 (11 days)
	1x Reach stacker 40 Ton	✓	☐	☐	The reach stacker 40 ton was functioning normally.	-
	1x Forklift 32 Ton	☐	☐	✓	A 32-ton forklift was found to be inoperable due to being hit by the tsunami.	12 November 2019 (45 days)
	2x Forklift 7 Ton	✓	☐	☐	Two 7-ton forklifts were found to be operating well.	-
	1x Forklift 5 Ton	✓	☐	☐	One 5-ton forklift was found to be operating well.	-
	1x Forklift 3 Ton	✓	☐	☐	One 3-ton forklift was found to be operating well.	-
	8x Head truck 40 Ton	✓	☐	☐	All eight 40-ton head trucks were functioning well.	-
	11x Chassis trailer	✓	☐	☐	All 11-trailer chassis were still functioning well.	-
	2x Forklift Battery	✓	☐	☐	Both battery-powered forklifts were still working well.	-
	Electricity power	☐	☐	✓	In the aftermath of the disaster, there was a complete power outage, including the supply to the Port of Pantoloan.	2 October 2018 (4 days)

Figure 28. PIDA results of the Technical Component of the Port of Pantoloan. For Degree of Damage, N = Not affected, P = Partially affected, T = Totally unusable

(a) **(b)**

Figure 29. Ships were stranded at the dock, preventing other ships from accessing it (a), and the quay crane collapsed at the Port of Pantoloan (b) (Courtesy of PT. Pelindo)

(a) **(b)**

Figure 30. Condition of the partial stacking yard area affected by tsunami (a), and condition of the other partial stacking yard area that can still be used (b) (Courtesy of PT. Pelindo IV)

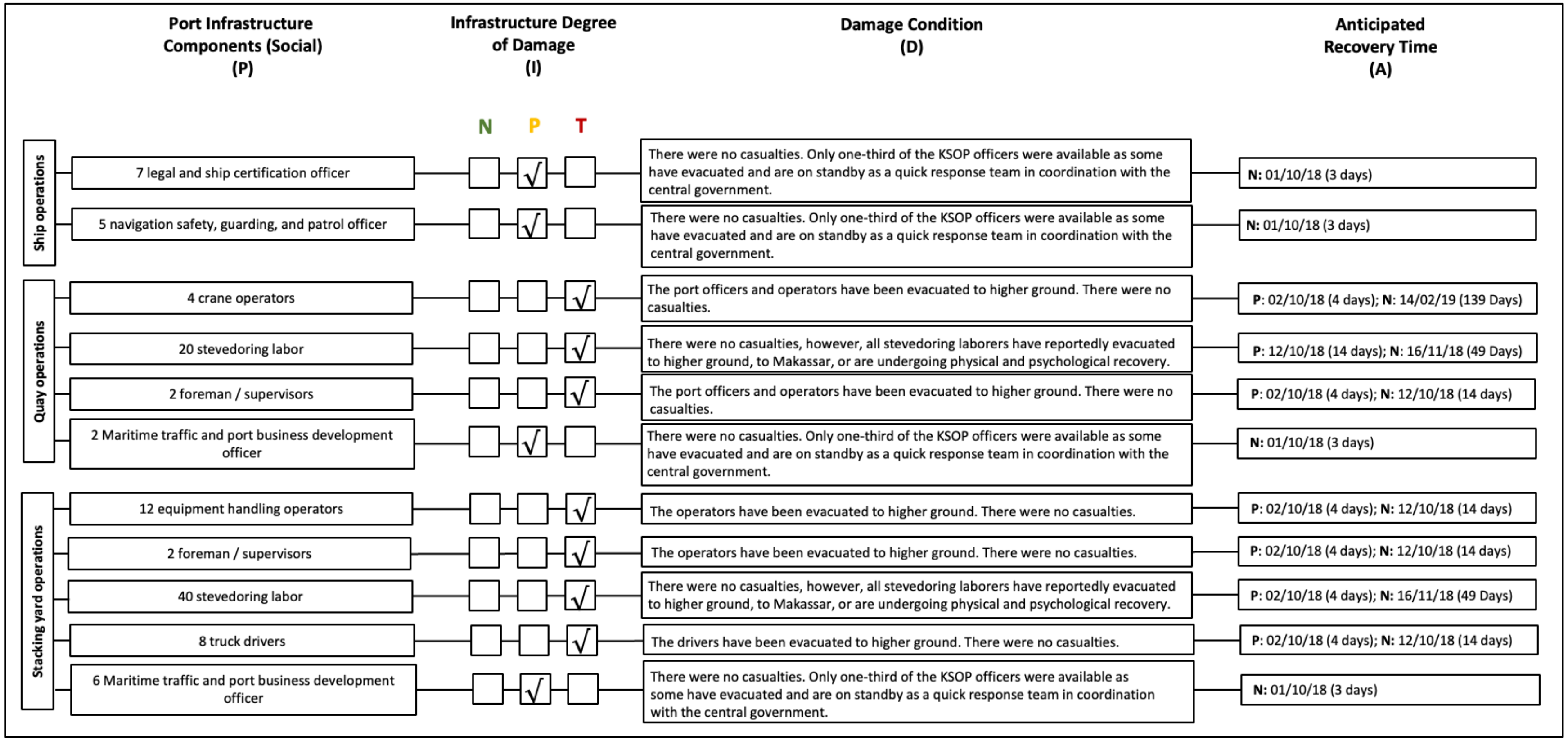
For the social components, the results of qualitative data processing using the PIDA sheet are shown in Figure 31. This social component analysis focuses on 3 port operational sections: Ship, Quay, and Stacking Yard Operations. These three parts of operations were chosen because they involve human resources directly from both the port authority and port operators, which are the first-layer actors of the Port of Pantoloan. The list of social components made using the block diagram in Figure 22 is reused to analyze the impact of the disaster on these components in this phase.

In general, the disaster had two impacts on the social components at Pantoloan Port. The first impact is partial damage, where the impact is experienced by the Port Authority, namely KSOP Class II Pantoloan. As a form of response to disaster response and as a representative of the central government, KSOP Class II Pantoloan assigned one-third of its staff to become part of the disaster response team and to stay at the port when the earthquake and tsunami had stopped and act as a representative to communicate with the central government for the response to the disaster. This has kept a partial portion of the port authority on standby since the first day after the disaster affected the Port of Pantoloan. The function of KSOP Class II Pantoloan was restored within three days after receiving rapid response personnel from the central government in Jakarta to increase the number of staff acting as a quick response team. The impact that resulted in the ‘totally damaged’ part of the social component was composed of the workers and laborers as port operators. The fact that port operators could not function was not due to casualties but due to the large number of affected houses in the hinterland. Thus, the impact of the earthquake and tsunami was more of an indirect impact as the damage was caused to the hinterland of Sulawesi Island by the earthquake and tsunami. The time needed for port operator employees such as crane operators, equipment handling operators, supervisors, and truck drivers to recover was about 14 days, while stevedoring labor took up to 49 days for a full recovery.

After analyzing the impact of the disaster on the technical and social components at the Port of Pantoloan using PIDA, the analysis results were converted back into the form of a block diagram. Figure 32 shows the block diagram of operations at the Port of Pantoloan at the t_d resilience curve point with blocks using color coding as in PIDA. By reusing the block diagram visualization, the results of the disaster impact analysis on the technical and social components of the Port of Pantoloan can be linked to its impact on the port operations processes.

Figure 32 shows that at point t_d, the Port of Pantoloan’s processes in the Quay and Stacking Yard Operations could not function completely. The first cause of the cessation at Quay Operations was the stranding of ships on the berth, the collapse of the ship-to-shore container crane, and the power failure as a direct impact of the earthquake and tsunami. The second cause was the unavailability of crane operators and stevedoring laborers. The disaster affected many of their homes, families, and relatives and they needed time to recover and get ready to continue to work again. The main cause of the cessation in the Stacking Yard Operations was more influenced by social components, such as the absence of operators and stevedoring labor needed to load and unload goods, where all employees of the port operator were victims of the magnitude of the natural disaster. The social components aspect is important because the technical aspects for stacking yard operations, apart from a 32-ton forklift and the electricity supply, were all still functional. This shows that it is necessary to identify the impact of a disaster not only on the technical components but also on the social aspects of the port to find the root cause of why an operation at the port was disrupted.

By using the results of the PIDA analysis in a block diagram, stakeholders can learn what the impact of the earthquake and tsunami was on the operations process of the Port of Pantoloan, as well as what components were the root causes that affected the port's operational processes. For ports with a similar context to the Port of Pantoloan, the results of this analysis can be used as a reference to the impact expectations when the port experiences a similar natural disaster.



	Port Infrastructure Components (Social) (P)	Infrastructure Degree of Damage (I) N	P	T	Damage Condition (D)	Anticipated Recovery Time (A)
Ship operations	7 legal and ship certification officer	☐	☑	☐	There were no casualties. Only one-third of the KSOP officers were available as some have evacuated and are on standby as a quick response team in coordination with the central government.	**N:** 01/10/18 (3 days)
	5 navigation safety, guarding, and patrol officer	☐	☑	☐	There were no casualties. Only one-third of the KSOP officers were available as some have evacuated and are on standby as a quick response team in coordination with the central government.	**N:** 01/10/18 (3 days)
Quay operations	4 crane operators	☐	☐	☑	The port officers and operators have been evacuated to higher ground. There were no casualties.	**P**: 02/10/18 (4 days); **N**: 14/02/19 (139 Days)
	20 stevedoring labor	☐	☐	☑	There were no casualties, however, all stevedoring laborers have reportedly evacuated to higher ground, to Makassar, or are undergoing physical and psychological recovery.	**P**: 12/10/18 (14 days); **N**: 16/11/18 (49 Days)
	2 foreman / supervisors	☐	☐	☑	The port officers and operators have been evacuated to higher ground. There were no casualties.	**P**: 02/10/18 (4 days); **N**: 12/10/18 (14 days)
	2 Maritime traffic and port business development officer	☐	☑	☐	There were no casualties. Only one-third of the KSOP officers were available as some have evacuated and are on standby as a quick response team in coordination with the central government.	**N:** 01/10/18 (3 days)
Stacking yard operations	12 equipment handling operators	☐	☐	☑	The operators have been evacuated to higher ground. There were no casualties.	**P:** 02/10/18 (4 days); **N:** 12/10/18 (14 days)
	2 foreman / supervisors	☐	☐	☑	The operators have been evacuated to higher ground. There were no casualties.	**P:** 02/10/18 (4 days); **N:** 12/10/18 (14 days)
	40 stevedoring labor	☐	☐	☑	There were no casualties, however, all stevedoring laborers have reportedly evacuated to higher ground, to Makassar, or are undergoing physical and psychological recovery.	**P:** 02/10/18 (4 days); **N:** 16/11/18 (49 Days)
	8 truck drivers	☐	☐	☑	The drivers have been evacuated to higher ground. There were no casualties.	**P:** 02/10/18 (4 days); **N:** 12/10/18 (14 days)
	6 Maritime traffic and port business development officer	☐	☑	☐	There were no casualties. Only one-third of the KSOP officers were available as some have evacuated and are on standby as a quick response team in coordination with the central government.	**N:** 01/10/18 (3 days)

Figure 31. PIDA results for Social Components of the Port of Pantoloan. For Degree of Damage, N = Not affected, P = Partially affected, T = Totally unusable

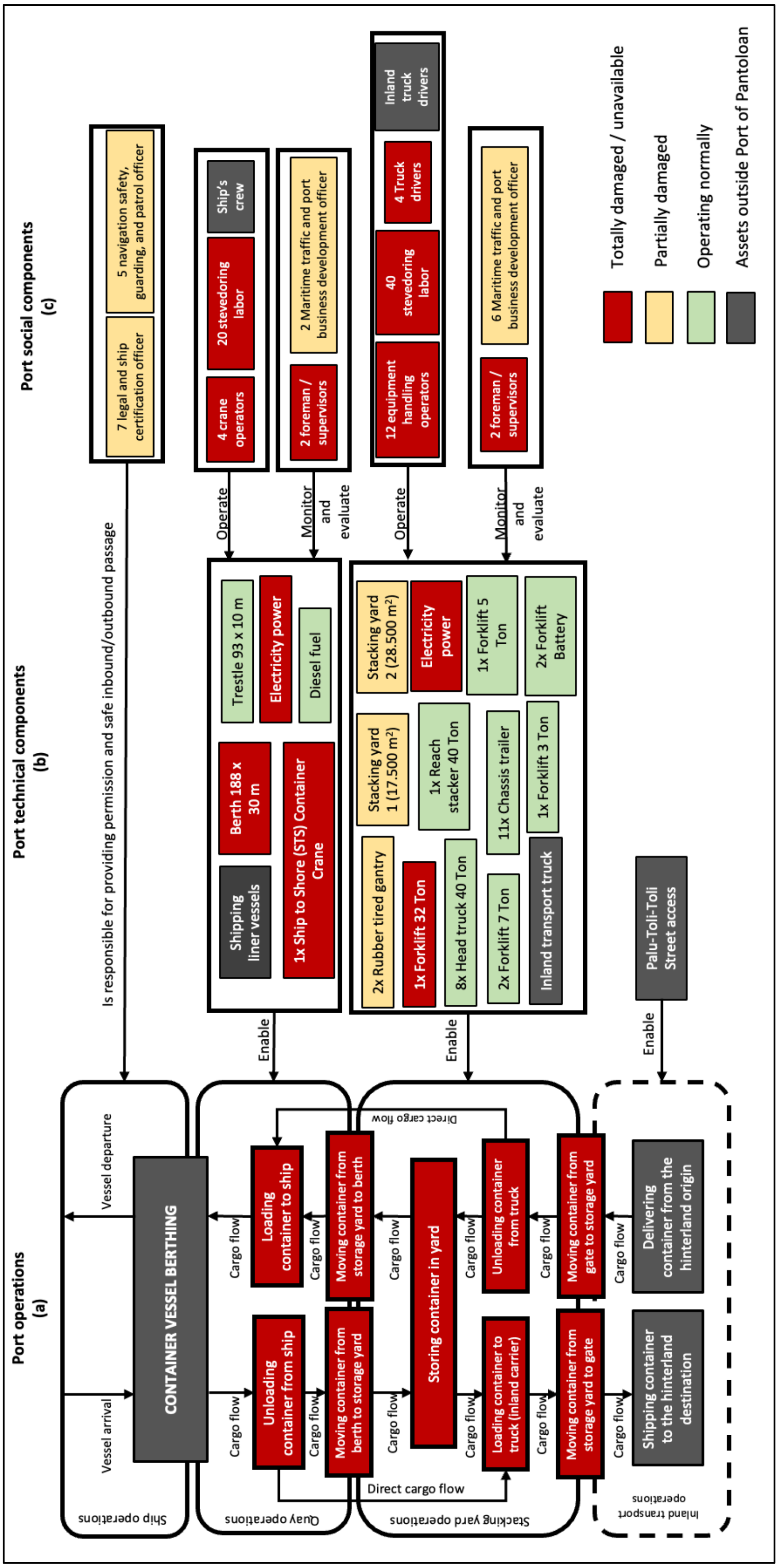


Figure 32. Block diagram of the Port of Pantoloan as a Socio-Technical System with added results from disaster impact analysis using PIDA

4.3.2 Disaster Impact Analysis on the Sulawesi Island's Ports-Hinterland Network Connectivity

In this subsection, we analyze the direct impact of the earthquake and tsunami on Ports-Hinterland connectivity on Sulawesi Island. The first thing that will be analyzed in this section is whether there is a change in the spare capacity replacement index at alternative ports on Sulawesi Island or $SCRI_p$. The change in $SCRI_p$ indicates whether the disaster impacts more than one port (multi-port impact). To analyze these changes, we processed data from seven press archives ([4-32] to [4-38]) related to damage reports at other ports and hinterland networks on Sulawesi Island. Based on the data we processed, the results of the $SCRI_p$ changes can be seen in Table 17. Changes in container service capacity at ports in Sulawesi following the disaster.

Table 17. Changes in container service capacity at ports in Sulawesi following the disaster

Container ports in Sulawesi	Daily Spare Capacity at the time t_d in TEUs ($SC_p(t_d)$)	Spare capacity replacement per port ($SCRI_p(t_d)$)	The time when spare capacity is recovered
Makassar	-	0%	14 October 2018 (16 days)
Kendari	377	46%	Not directly / indirectly affected by disaster
Bitung	311	38%	
Gorontalo	139	17%	
Luwuk	27	3%	
Toli-Toli	16	2%	
Anggrek	15	2%	
Malili	9	1%	
Pare-Pare	7	1%	

Based on the analysis, we found that the Port of Makassar, which was initially projected to be able to receive the diverted vessels originating from the Port of Pantoloan with a $SCRI_p$ value of 100%, could not be used at all after the disaster. This is not because the infrastructure in the Port of Makassar was directly affected by the disaster but because of the Regional Government's implementation of an emergency conditions decree on Sulawesi Island. With the implementation of this decree, the Port of Makassar was temporarily used as a hub for evacuating Central Sulawesi communities affected by the disaster, as shown in Figure 33. This lasted two weeks (16 days), during which the Port of Makassar received approximately 4,000 refugees from Palu and the Central Sulawesi province.

In addition, the Port of Makassar was also used as a relief distribution hub and transfer point for refugees who wanted to leave Sulawesi Island. What happened to the Port of Makassar shows the indirect impact of disasters, especially when the disaster is large-scale and has many casualties; the largest port in the region is prioritized for humanitarian aid distribution first instead of commercial services. Meanwhile, Alternative Ports on Sulawesi Island were not directly or indirectly affected by the disaster, and $SCRI_p$ for each port remained unchanged.

Figure 33. The appearance of the Port of Makassar when receiving refugees from Palu and Central Sulawesi Province (courtesy of PT. Pelindo IV)

The next analysis is to calculate whether there was a difference in the hinterland infrastructure that connects the Port of Pantoloan with other alternative ports on Sulawesi Island caused by the direct or indirect impact of the disaster. The number of trucks (1 TEU) needed to capture the port spare capacity per day after disaster ($N_p(t_d)$) will be analyzed further to measure this. To determine the value of ($N_p(t_d)$), the direct impact of the disaster on the hinterland network will be analyzed first. Data from field surveys conducted by the Ministry of Public Works and Housing (PUPR) and independent research institutions are used in this analysis. Table 18 lists which road sections were directly affected by the disaster and how the disaster affected the average one-way travel time, or dt_p in minutes.

Based on the results of the data analysis, we found that the impact of the disaster on the hinterland network was extensive and affected many roads connecting the Port of Pantoloan with other alternative ports on Sulawesi Island. The first route that was heavily impacted was connecting the Port of Pantoloan with alternative ports in the North, such as the Port of Toli-Toli, Anggrek, Bitung, and Gorontalo. One of the roads that was significantly affected was the Trans Sulawesi road, which is close to the epicenter of the earthquake. On the Trans Sulawesi road in the north, especially in Enu Village, the main road connecting the Port of Pantoloan with alternative ports was buried by landslides.

The condition of the landslide-covered Trans Sulawesi road that occurred in Enu Village can be seen in Figure 34. This situation disrupted travel to and from the Port of Pantoloan from alternative ports in the north. For example, before the disaster, the fastest way to connect the Port of Toli-Toli with the Port of Pantoloan was through Trans Sulawesi road, which took about 519 minutes. However, after the disaster, this road was covered by landslides, resulting in one trip taking an average of 1,116 minutes caused by traffic congestion. This resulted in the preference shifting of the route from Trans Sulawesi to Toli-Toli - Palu road which takes 798 minutes, different from the preference of road use during normal conditions. This significant increase in dt_p occurred not only for the Port of Pantoloan - Toli-Toli route but also on routes connecting the Port of Pantoloan with other ports in North Sulawesi.

Table 18. The impact of the earthquake and tsunami on the road network in Sulawesi Island at point t_d

No	Origin - Destination	Name	Terrain / Type	Condition	Average one-way Travel Time (Min), dt_p after disaster
1	Toli-Toli - Pantoloan	Jl. Toli-Toli - Palu (Route 1)	Coastal flat road	Road cracks	798
2	Toli-Toli - Pantoloan	Jl. Trans Sulawesi (Route 2)	Mountain/hilly road	Covered in landslides	1,116
3	Anggrek - Pantoloan	Jl. Trans Sulawesi	Mountain/hilly road	Covered in landslides	2,203
4	Bitung - Pantoloan	Jl. Trans Sulawesi	Mountain/hilly road	Covered in landslides	2,789
5	Gorontalo - Pantoloan	Jl. Trans Sulawesi	Mountain/hilly road	Covered in landslides	2,045
6	Luwuk - Pantoloan	Jl. Trans Sulawesi	Mountain/hilly road	Normal	745
7	Kendari - Pantoloan	Jl. Trans Sulawesi	Mountain/hilly road	Normal	1,139
8	Bau-Bau - Pantoloan	-	-	-	-
9	Malili - Pantoloan	Jl. Trans Sulawesi	Mountain/hilly road	Normal	660
10	Makassar - Pantoloan	Jl. Poros Majene - Mamuju (Route 1)	Coastal flat road	Road cracks	Not passable by trucks
11	Makassar - Pantoloan	Jl. Trans Sulawesi (Route 2)	Mountain/hilly road	Normal	1,279
12	Pare-Pare - Pantoloan	Jl. Poros Majene-Mamuju (Route 1)	Coastal flat road	Road cracks	Not passable by trucks
13	Pare-Pare - Pantoloan	Jl. Trans Sulawesi (Route 2)	Mountain/hilly road	Normal	1,109

Figure 34. The Trans-Sulawesi road, which connects Palu to Tolitoli and other northern port alternatives, was obstructed due to a landslide in Enu Village

As for the section of the route connecting the Port of Pantoloan with ports in the south, the impact of the disaster was directly identified on the Majene - Mamuju axis road segment, where several cracks occurred due to the earthquake. The cracks made it impossible for trucks to use the road and they had to take an alternative route through the hills. It was reported that there were no landslides on the hilly road that connects the Port of Pantoloan with container ports in the southern part of Sulawesi Island. By knowing the impact of the earthquake and tsunami disaster on the roads on Sulawesi Island, one needs to know how many resource trucks (with a capacity of 1 TEU), $N_p(t_d)$, are needed to capture the spare capacity of the alternative port after the disaster.

Table 19. Number of trucks needed to capture the port spare capacity per day after disaster

Port	**Daily Available spare capacity (TEU) Daily (SC_p)**	**Average Round trip travel time in Hour (dt_p)**	**Number of trucks (1 TEU) needed to capture the port spare capacity per day ($N_p(t_d)$) after disaster**
Makassar	0*	49.6	-
Kendari	377	38.0	597 (Unchanged)
Bitung	311	97	1,256 (+935 trucks)
Gorontalo	139	72.1	417 (+269 trucks)
Luwuk	27	24.8	28 (Unchanged)
Toli-Toli	16	28.6	19 (+8 trucks)
Anggrek	15	75.4	47 (32 trucks)
Malili	9	22.0	8 (Unchanged)
Pare-Pare	7	42.3	12 (+2 trucks)

*) Spare capacity at the Port of Makassar cannot be used because the port is prioritized as a hub for receiving refugees affected by the tsunami and earthquake from Central Sulawesi, as well as a hub for the distribution of humanitarian aid on Sulawesi Island.

Based on the disaster impact analysis results on ports-hinterland network connectivity in Sulawesi Island, we found no change in the daily available spare capacity at the ports in northern Sulawesi. However, we found that more resource trucks were required to access this spare capacity. For example, to access the spare capacity at the Port of Bitung, an additional 935 trucks per day would be needed, and to access the spare capacity at the Port of Gorontalo, an additional 269 trucks per day would be required. Meanwhile, access to spare capacity at ports in South Sulawesi, especially the Port of Makassar, was temporarily unavailable for commercial vessels because it was prioritized for refugee transit points and humanitarian aid distribution. The port with spare capacity and accessibility unaffected by the disaster was the Port of Kendari. The port is located in Southeast Sulawesi, far from the earthquake epicenter. Based on these findings, the Port of Kendari was an ideal port to divert commercial vessel traffic from the Port of Pantoloan, which was affected by the earthquake and tsunami.

4.3.3 Disaster Impact Analysis on Sulawesi Island's Shipping Network Connectivity

This subsection will analyze the impact of disasters on shipping network connectivity for Sulawesi Island. The analysis procedure is the same as determining shipping network connectivity in phase 1 (can be seen in subsection 4.1.3). The primary difference in the analysis lies in the analysis timeframe used. In this analysis, two timeframes are used. The first timeframe is when the port performance is in the response phase ($[t_d, t_{s2}]$) and the second timeframe is when the performance is in the recovery phase ($[t_{s2}, t_{f2}]$).

We used data extracted from AIS from September 29, 2018 to July 31, 2019 to analyze changes in shipping network connectivity on Sulawesi Island. The ships included in this analysis are only commercial container ships, while cargo ships for humanitarian assistance are not included. Based on the AIS data that has been obtained, the connectivity for each port in Sulawesi Island in the response phase and recovery phase is calculated using Equation (3), then the accumulation of the connectivity of each port is used as the basis for determining the connectivity of Sulawesi Island as shown in Equation (4). Table 20 shows the shipping connectivity of container ports on Sulawesi Island during the response phase ($[t_d, t_{s2}]$) and the extent of the change compared to normal conditions.

Table 20. The connectivity of container ports on Sulawesi Island during the response phase ($[t_d, t_{s2}]$) (138 days) compared to the daily average of normal conditions in 2018 before the disaster

Rank	**Port**	**Port's shipping connectivity (in TEU)**	**Average port's shipping connectivity per day (TEU/day)**	**Change of port's shipping connectivity per day (TEU/day)**
1	Makassar	339,740	2462	+346 (+16%)
2	Bitung	72,604	526	+4 (+1%)
3	Anggrek	54,308	394	+3 (+1%)
4	Kendari	50,696	367	+50 (+16%)
5	Pantoloan	42,083	319	-520 (-63%)
6	Toli-Toli	18,587	135	+51 (+60%)
7	Bau-Bau/Murhum	16,639	121	+1 (+1%)
8	Luwuk	15,594	113	+1 (+1%)
9	Gorontalo	11,458	110	-1 (-1%)
10	Pare-Pare	3,450	25	-1 (-4%)
11	Malili	2,760	20	-1 (-6%)
Sulawesi Island's connectivity		**627,919**	**4,550**	**-95 (2%)**

In the response phase ($[t_d, t_{s2}]$), it can be found that with the disruption of the Port of Pantoloan, the maritime shipping connectivity on Sulawesi Island decreased by about 2%. Indeed, many alternative ports had spare capacity to accommodate traffic diverting from the Port of Pantoloan, so the decline in shipping connectivity on Sulawesi Island was less pronounced. Based on the results of empirical analysis, the Port of Pantoloan lost shipping connectivity per day by up to 63% compared to normal conditions, or around 520 TEUs per day.

To facilitate the inflow and outflow of goods from Sulawesi Island due to the disruption of operational activities at the Port of Pantoloan, the Port of Makassar in southern Sulawesi became an alternative port with the largest average addition of shipping connectivity compared to other alternative ports. In the first two weeks after the disaster, the Port of Makassar did not receive any services for commercial ships. After lifting the emergency status, the Port of Makassar became the primary port for ships that formerly stopped at the Port of Pantoloan. The Port of Makassar experienced an increase in container loading and unloading, with an average of approximately 346 TEUs daily.

Table 21 shows how the routes of commercial container ships changed when the Port of Pantoloan performance was in the response phase timeframe ($[t_d, t_{s2}]$). We use three types of responses from commercial shipping services to map changes in inbound links to Pantoloan port. The first type of response is rerouting, which explains that ships go to ports that weren't originally on their fixed schedule. The second type of response is skipping, where ships directly head to the next port on their scheduled route without adding a new port destination. The third response type is unchanged, where the Port of Pantoloan remains the destination for loading and unloading goods. Small-size vessels usually use this response.

Table 21. Changes in shipping services connected to the Port of Pantoloan during the response phase $[t_d, t_{s2}]$

Initial inbound service	Change of inbound service	% Estimation of Shipping capacity (TEU)	Type of response
Ambon – Pantoloan	Ambon – Kendari	12%	Rerouting
	Ambon – Makassar	78%	Rerouting
	Ambon – Pantoloan	10%	Unchanged
Semarang – Pantoloan	Semarang – Makassar	84%	Rerouting
	Semarang – Pantoloan	7%	Unchanged
	Semarang – Samarinda	9%	Skipping
Tarakan – Pantoloan	Tarakan – Makassar	73%	Rerouting
	Tarakan – Pantoloan	6%	Unchanged
	Tarakan – Toli-Toli	21%	Skipping
Kuala Tanjung – Pantoloan	Kuala Tanjung – Makassar	100%	Rerouting
Tenau/Kupang – Pantoloan	Tenau/Kupang – Makassar	100%	Rerouting
Wini – Pantoloan	Wini – Pantoloan	100%	Unchanged
Tanjung Perak – Pantoloan	Tanjung Perak – Pantoloan	100%	Unchanged
Anggrek – Pantoloan	Anggrek – Makassar	100%	Rerouting
Nunukan – Pantoloan	Nunukan – Toli-Toli	100%	Skipping
Toli-Toli – Pantoloan	Toli-Toli – Makassar	100%	Skipping
Banjarmasin – Pantoloan	Banjarmasin – Pantoloan	30%	Unchanged
	Banjarmasin – Makassar	70%	Rerouting
Samarinda – Pantoloan	Samarinda – Makassar	100%	Rerouting

Based on the results obtained in Table 21, it is found that the Port of Makassar was used as the main alternative destination when the Port of Pantoloan could not operate because it had a large spare capacity for loading and unloading containers and the closure of the access road to the alternative port in the north also caused many container loading and unloading activities to switch to the Port of Makassar. In addition, most inbound links to Pantoloan are large ports located in the western, southern, or southeastern regions of Sulawesi Island. The ports in these areas are closer to the Port of Makassar than other alternative container ports in the island's northern part. As for shipping services originating from the northern region of Sulawesi or Kalimantan, the Port of Toli-Toli was the main alternative for loading and unloading goods previously intended for the Port of Pantoloan.

Meanwhile, loading and unloading of shipping services originating from the eastern region were carried out at the Port of Kendari, located in the eastern part of Sulawesi Island. Based on the results of empirical analysis, the selection of alternative ports considers three things: sufficient spare capacity, adequate hinterland access conditions, and distance (or cost) calculations that are closer or more acceptable to shipping operators. Table 22 shows how shipping connectivity changed on Sulawesi Island when the operational performance of Pantoloan Port was in the recovery phase ($[t_{s2}, t_{f2}]$). In this recovery phase, the loading and unloading capacity of Pantoloan Port has returned to normal. Still, the Port of Pantoloan traffic has not yet reached the level before the disaster. The recovery phase lasted 157 days, from February 14 to July 21, 2019.

Table 22. The connectivity of container ports on Sulawesi Island during the recovery phase ($[t_{s2}, t_{f2}]$) compared to the daily average of normal conditions in 2018 before the disaster

Rank	**Port**	**Port connectivity (in TEU)**	**Average connectivity per day (TEU/day)**	**Change of connectivity per day (TEU/day)**
1	Makassar	356,761	2272	+156 (+7%)
2	Pantoloan	93,446	595	-229 (-28%)
3	Bitung	82,005	522	0
4	Anggrek	61,341	391	0
5	Kendari	51,339	327	10 (+3%)
6	Bau-Bau/Murhum	18,794	120	0
7	Luwuk	17,609	112	0
8	Gorontalo	17,426	110	0
9	Toli-Toli	13,201	84	0
10	Pare-Pare	4,070	26	0
11	Malili	3,349	21	0
Sulawesi Island's connectivity		**719,341**	**4,593**	**-52 (-1,1%)**

The analysis results for the recovery phase ($[t_{s2}, t_{f2}]$) show that shipping connectivity on Sulawesi Island gradually recovered and was getting closer to the connectivity before the disaster. This improved connectivity was driven by the Port of Pantoloan's return capacity to load and unload containers by replacing quay cranes damaged by the tsunami. In this phase, the Port of Pantoloan served around 70% of the initial traffic, with the Port of Makassar still serving as a buffer to support the loading and unloading capacity at the Port of Pantoloan. However, the amount of traffic from the Port of Pantoloan served by the Port of Makassar in this phase had already been reduced compared to the response phase. Meanwhile, the Port of Kendari still experienced a slight increase in traffic compared to its normal average conditions.

Table 23 shows the changes in shipping services in the recovery phase ($[t_{s2}, t_{f2}]$) compared to normal conditions. The table adds one type of response category: returning *to the initial trajectory*. This category means that the ships that have returned are ships that rerouted to other ports or skipped the Port of Pantoloan in the previous phase (response phase). For example, on the Port of Semarang - Pantoloan route, 33% of the shipping service capacity was found to have returned to the Port of Pantoloan from previously choosing to unload at the Port of Makassar as an alternative port. The remaining 67% still decided to load and unload containers at the Port of Makassar. Based on the analysis results, we found that the shipping services that return to the Port of Pantoloan are shipping services that connect the Port of Pantoloan with ports nearby, such as on Kalimantan Island and also ports on the north side of Sulawesi. Generally, these ports use medium-sized container ships (1,000 - 2,000 DWT). Large ships originating from Hub ports in Indonesia, such as the Port of Semarang, Kuala Tanjung, Tenau/Kupang, and Ambon, measuring more than 2,000 DWT, still use the Port of Makassar for shipping containers destined for the Central Sulawesi region. In contrast, medium-sized ships have gradually returned to the Port of Pantoloan.

Table 23. Changes in shipping services connected to the Port of Pantoloan during the response phase $[t_d, t_{s2}]$

Initial inbound trajectory	Response link	% Estimation of Shipping capacity (TEU)	Type of response
Ambon - Pantoloan	Ambon - Kendari	5%	Rerouting
	Ambon - Makassar	25%	Rerouting
	Ambon - Pantoloan	70%	Unchanged
Semarang - Pantoloan	Semarang - Makassar	67%	Rerouting
	Semarang - Pantoloan	33%	Return to the initial trajectory
	Semarang - Samarinda	0%	-
Tarakan - Pantoloan	Tarakan - Makassar	29%	Rerouting
	Tarakan - Pantoloan	71%	Unchanged
	Tarakan - Toli-Toli	10%	Skipping
Kuala Tanjung - Pantoloan	Kuala Tanjung - Makassar	28%	Rerouting
	Kuala Tanjung - Pantoloan	72%	Return to the initial trajectory
Tenau/Kupang - Pantoloan	Tenau/Kupang - Makassar	20%	Rerouting
	Tenau/Kupang - Pantoloan	80%	Return to the initial trajectory
Wini - Pantoloan	Wini - Pantoloan	100%	Unchanged
Tanjung Perak - Pantoloan	Tanjung Perak - Pantoloan	100%	Unchanged
Anggrek - Pantoloan	Anggrek - Makassar	5%	Rerouting
	Anggrek - Pantoloan	95%	Return to the initial trajectory
Nunukan - Pantoloan	Nunukan - Toli-Toli	100%	Skipping
Toli-Toli - Pantoloan	Toli-Toli - Makassar	100%	Skipping
Banjarmasin - Pantoloan	Banjarmasin - Pantoloan	100%	Return to the initial trajectory
	Banjarmasin - Makassar	0%	-
Samarinda - Pantoloan	Samarinda - Makassar	0%	-
	Samarinda - Pantoloan	100%	Return to the initial trajectory

In summary, the disaster impact analysis conducted on shipping connectivity for Sulawesi Island can tell how much influence the disruption of the Port of Pantoloan’s operations had on the inflow and outflow of goods of Sulawesi Island. Based on the analysis results, the impact of the disaster on Sulawesi Island's connectivity for container shipping was relatively small, decreasing only by 2% or losing around 95 TEUs daily. This was in spite of the fact that the container crane at the Port of Pantoloan could not operate. This small decrease can be explained because Sulawesi Island has many container ports spread across various regions in Sulawesi. The Port of Makassar is the main alternative port used by commercial shipping services to replace the Port of Pantoloan role, especially with routes connected to hub ports in western Indonesia (Sumatra and Java) and south (Nusa Tenggara Islands). Other ports used to replace the Port of Pantoloan include Toli - Toli and Kendari ports that connect shipping services with the northern (Kalimantan Island), and eastern (Maluku Islands) regions of Sulawesi Island.

The disaster impact analysis was also conducted in the phase where the container loading and unloading capacity of the Port of Pantoloan had returned with the new quay cranes. In this phase, shipping services originating from ports in the west, north, and east re-routed their voyages and connected again with Pantoloan Port. This shipping service is generally carried out by medium-sized ships and has a relatively short distance. Meanwhile, ships originating from national hub ports such as from the West (Sumatra and Java) and the South (East Nusa Tenggara) have also diverted part of the voyage to the Port of Pantoloan, but for large vessels they still use the Port of Makassar Port as an alternative port of loading and unloading. The shipping connectivity on Sulawesi Island in this phase increased as well, where previously there was a decrease of 2%; however, during this phase, the overall decrease was only 1.1%.

4.4 Phase 4: Resilience Intervention Analysis

This section explains what interventions were carried out to improve the resilience of the Port of Pantoloan and who the actors involved in these interventions were. Two types of interventions were analyzed in this section. The first is port-level interventions (L1), and the second is island-level transportation network connectivity interventions (L2). This analysis will be useful to determine how these interventions affect the behavior of port operations and their resilience.

A qualitative content analysis technique is employed to conduct this analysis. The data used in this phase are five field study reports, 44 mass media articles, and three official reconstruction and rehabilitation plan documents from the port operator (See the list of documents at the end of this chapter for more details from [4-39] to [4-90]). The intervention data we collected will then be categorized based on the time phase of the resilience cycle: preparation phase ($t < t_e$), response phase ($[t_e, t_s]$ or $[t_d, t_s]$), recovery phase ($[t_s, t_f]$), and adaptation phase ($t > t_f$). In each phase of the resilience cycle, the interventions will be sorted based on the time order in which they were taken, and information will be added regarding the main actors involved, the type of theoretical category related to the intervention, and whether the intervention category is L1 (port level) or L2 (island level). The next subsection will explain the analysis of the resilience interventions taken in each phase of the resilience cycle.

4.4.1 Resilience Intervention Analysis in the Preparation Phase ($t < t_e$)

This subsection analyzes what resilience interventions were carried out at the port level (L1) or the island transport network level (L2) before the disaster. The list of interventions carried out in this preparation phase is shown in Table 24. The table lists all resilience interventions carried out to improve port resilience, the timing of the interventions, the theoretical intervention categories, and the actors involved.

Based on the data that has been analyzed, five interventions were carried out as mitigation efforts before the disaster occurred. Of the five known interventions, only one focused on infrastructure preparedness, while the other four focused on process preparedness. The operators of the Port of Pantoloan generally have an awareness that port development in the Central Sulawesi region is one of the areas that has been prone to earthquakes since 1828. However, due to budget constraints in developing earthquake-resistant port infrastructure, the port operator and KSOP Class II Palu Bay made preparations that did not require a large budget. One of the things done by the Port of Pantoloan's operator is to procure spare capacity of cargo handling equipment such as reach stackers and forklifts as a backup for when the cranes in the stacking yard are not functioning. Apart from increasing the capacity of handling equipment for cargo, no other interventions related to infrastructure preparedness were carried out at the Port of Pantoloan.

An intervention that was carried out to answer the challenges of the tight development budget of the Port of Pantoloan was to focus on process preparedness. One of the visible intervention efforts is focusing on personnel training of port employees and stevedores in recognizing signs and being able to evacuate themselves. Some of the preparations made include training employees to be able to read the tsunami signs and how to evacuate themselves (the training has been conducted since 2014), and training employees to interpret messages related to climate change and weather from the Meteorology and Geophysics Agency (BMKG) since 2016. In addition, to strengthen the information exchange for real-time monitoring of disaster projections, the Port of Pantoloan operators coordinate with the Indonesian Institute of Science (LIPI) every year to hear the latest developments on the Sulawesi fault plate. In addition, the port operator also strengthened coordination with BMKG regarding the exchange of disaster projection data supported by the installation of a mobile application specifically designed for the Port of Pantoloan operator, which began in 2016, which is two years before the disaster occurred. In addition to the interventions mentioned above, no other interventions were found, especially at the network level, which were made specifically to support the resilience of the Port of Pantoloan to natural disasters.

Table 24. Resilience interventions during the preparation phase ($t < t_e$). For the intervention category. Hard = Hardening, Red = Redundancy, Mod = Modularity, CT = Capacity Tolerance, PT = Personnel Training, RP = Response Planning, Coord = Coordination, Coop = Cooperation

No	**Resilience interventions and level category**	**Time taken (Before t_e)**	**Category**								**Actors involved**
			Infrastructure Preparedness				**Process Preparedness**				
			Hard	**Red**	**Mod**	**CT**	**PT**	**RP**	**Coord**	**Coop**	
1	Port of Pantoloan personnel have undergone training to conduct evacuations during tsunami warnings (L1)	Once a year, since 2014					√				Port operator
2	Personnel at the Port of Pantoloan have been trained to interpret and respond to messages from the Meteorology, Climatology, and Geophysics Agency (BMKG) (L1)	Twice a year, since 2015					√				Port operator; BMKG
3	The Port operator has coordinated with the Indonesian Institute of Sciences (LIPI) to obtain recent research about a fault plate in Sulawesi Island for monitoring the disaster trend (L1)	Since 2015							√		Port operator; LIPI
4	Provide reach stackers and forklifts more than normal capacity needed as backups for fluctuating demand or damaged equipment (L1)	January 2016		√							Port operator
5	Port staff have equipped their mobile phones with digital early warning applications provided by the Central Sulawesi BMKG (L1)	Since 2016							√		Port operator

4.4.2 Resilience Intervention Analysis during Response Phase [t_d, t_s]

This section will discuss resilience intervention in the response phase. Overall, the response phase in this case study began on September 29, 2018 (point t_d) and continued until February 14, 2019 (at point t_{s2}), with a total duration of 138 days. The response phase started at point t_d due to the earthquake and tsunami disasters that occurred suddenly, interventions could not be carried out from point t_e, but could only be taken after the disaster occurred or more precisely at point t_d. The response phase in the Port of Pantoloan case study is divided into two parts to structure the intervention analysis. Response phase 1 is when the Port of Pantoloan had a disaster emergency status from September 29, 2018 (point t_d) to October 12, 2018 (point t_{s1}), with a duration of 13 days. Meanwhile, response phase 2 is the period where the port reopened services for commercial vessels with limited capacity on October 13, 2018 (point t_{f1}) until the Port of Pantoloan was ready again to open services with full capacity as before the disaster on February 14, 2019 (point t_{s2}) with a duration of 125 days. Table 25 and Table 26 lists the resilience interventions in response phase 1 and response phase 2, respectively.

In response phase 1, the resilience intervention of the Port of Pantoloan focused on gathering the resources needed to repair the prioritized physical infrastructure to enable the Port as a hub for the distribution of humanitarian aid, especially to those affected by the disaster in Central Sulawesi. Due to the magnitude of the impact of the natural disaster, the Port of Pantoloan was designated with emergency status by the Port Authority. This emergency status means the port did not serve commercial shipping and only served for humanitarian purposes for 13 days. The emergency status was established directly after the earthquake and tsunami on September 28, 2018. The decision of this disaster emergency status followed the Decree of the Governor of Central Sulawesi Number 466/425/BPD/2018, which mandated the Port of Pantoloan as a hub for humanitarian assistance and transportation of refugees from Palu City to other areas in Indonesia.

After being designated as a port with emergency status, the port operator temporarily closed port access to assess the impact of the disaster on the Port of Pantoloan, the results of which can also be seen in the disaster impact analysis in section 4.3. The physical infrastructure prioritized to be repaired as quickly as possible in response phase 1 was the debris-covered berth, stacking yard, and access road to the Port of Pantoloan from alternative ports to distribute humanitarian aid. To overcome the lack of resources to repair the physical infrastructure, the port operator and KSOP Class III Palu Bay cooperated with several parties outside the port. For example, to clean up the debris and remove stranded ships at the berth due to the tsunami, the port operator collaborated with the Indonesian National Army (TNI) to accelerate the debris cleaning process. This cooperation was considered effective when, on October 1, 2018, the Port of Pantoloan was reopened to receive humanitarian aid from all over Indonesia. One of the large-scale humanitarian aid shipments to the Port of Pantoloan began on October 2, when two military ships, namely KRI Dr. Suharso-990 and KRI Makassar-590, docked at the Port of Pantoloan with humanitarian aid.

At the same time, the Ministry of Public Works and Housing offices in Sulawesi were actively opening landslide-covered roads. These prioritized roads connect the Port of Pantoloan with the Port of Kendari and the Port of Makassar. One of the reasons for prioritizing the repair of cracked roads or roads buried by landslides was to facilitate the mobilization of material resources and volunteers to help with the repairs of the Port of Pantoloan. On October 3, some of these critical roads were already passable by small and medium-sized vehicles.

After the berths at the Port of Pantoloan and also the vital roads connecting the Port of Pantoloan with alternative container ports in Sulawesi, such as the Port of Makassar and Kendari, were accessible, the Ministry of Transportation was repurposing public service obligation vessels, such as KN Pasatimpo, KN Gandiwa, KM Lambelu, KM Labobar, and KM Camara Nusantara 3, which were previously used to serve inter-island shipping. These ships were diverted to help distribute humanitarian aid to the Port of Pantoloan. These ships not only carried relief goods for natural disaster victims but were also used to transport machinery and tools used to repair the physical infrastructure of the Port of Pantoloan.

To accelerate the repair of the Port of Pantoloan’s physical infrastructure, the Ministry of Transportation also provided many subsidies for PT. Pelni ships to waive tariffs for volunteers who wanted to help repair the affected port or to support disaster recovery activities in Central Sulawesi. This intervention brought in many civilian volunteers to help clean up the Port of Pantoloan, such as cleaning stacking yards and roads in Pantoloan port so that the port could be reused to serve commercial shipping on October 12, 2018 for 24 hours a day. However, the container handling capacity of these commercial vessels was still limited to around 30% of its initial capacity due to the collapse of the quay crane.

Response phase 2 started on October 13, 2018, when the Port of Pantoloan was reopened with limited capacity to serve commercial vessels. In this phase, the resilience intervention was focused on restoring the port's container handling capacity to normal. The limited capacity of the Port at that time caused heavy congestion of container ships that wanted to dock at Pantoloan. Most container ships that dock at Pantoloan port have a 500 - 700 TEU capacity with on-board cranes. Loading and unloading of containers can be done even without quay cranes, although the loading and unloading speed is significantly lower. Meanwhile, larger vessels with a capacity of more than 1,000 TEUs diverted to alternative container ports on Sulawesi Island to avoid congestion at the Port of Pantoloan.

The port operator and authority conducted several resilience interventions to overcome ship congestion and to restore the Port of Pantoloan to its original capacity. The first intervention was to remove the quay crane that collapsed due to the tsunami. After the quay crane was successfully removed, the port operator and port authority considered several options to restore the Port of Pantoloan’s container handling capacity. One option was to move the existing quay crane at the Port of Bitung to the Port of Pantoloan. This option was chosen because the container loading and unloading demand at Bitung is not as high as Pantoloan. In addition, moving the quay crane required a relatively lower cost than buying a new container quay crane. The agreement to move the quay crane was reached at the end of October 2018.

Technical planning related to the quay crane transfer between Pantoloan and Bitung Port operators began in early November 2018 and the crane was initially planned to be transferred in mid-November 2018. However, this process was delayed due to the ongoing need to accommodate humanitarian aid ships and the floating hospital, Nusa Waluya II, which docked at the Port for a month to assist local communities. By the end of November 2018, the operator of Port of Pantoloan received a visit from the Deputy Chair of Commission V of the Indonesian House of Representatives. He raised concerns from Palu business owners about a price surge for building materials and cement, which was essential for Palu's rebuilding after the disaster. To follow up on the situation, the operator of the Port of Pantoloan decided to invest in reach stackers and handling equipment in December 2018, aiming to expedite the unloading process in the stacking yard and to enhance port productivity.

On January 9, 2019, the quay crane from the Port of Bitung was prepared for relocation to the Port of Pantoloan using a barge. The journey took ten days, with the crane arriving at Pantoloan on January 20, 2019. The unloading and installation of the new quay crane took over a week, and on January 29, 2019, port operators announced that the new crane was in place. However, three days later, the crane was declared damaged and not fully operational due to mishandling during its relocation and unloading process. After repairs and testing, the newly relocated quay crane at Pantoloan Port from Bitung Port finally became fully operational on February 13, 2019.

Table 25. Resilience intervention during response phase 1 $[t_d, t_{s1}]$. For the intervention category. Repu = Repurposing, Reloc = Relocation, Repa = Reparation, Recon = Reconstruction, OF = Operational Flexibility, OA = Organizational Agility

No	**Resilience interventions and level category**	**Time taken** $[t_d - t_{s1}]$	**Category**						**Actors involved**
			Infrastructure adaptation				**Process adaptation**		
			Repu	**Reloc**	**Repa**	**Recon**	**OF**	**OA**	
1	A few hours after the disaster struck, the port operators closed the Port of Pantoloan to assess port infrastructure functionality (L1).	28-Sep-18					√		Port operator
2	The CEO of Pelindo IV announced formal directives to general managers, employees, and staff at Pantoloan Port to clean the port area, passenger terminal, and access points, which were obstructed by debris and containers from the storage yard (L1).	29-Sep-18						√	Port operator
3	The Port operator contacted the state-owned electric company to prioritize the electrical supply to the Port of Pantoloan for making it operational at night (L1)	29-Sep-18						√	Port operator, state-owned electrical company
4	The Port operator decided to invite and collaborate with the Main Naval Base VI (Lantamal) and Palu Naval Base to clear the remaining rubble and waste covering the berth segments and trestle (L1)	30-Sep-18			√			√	Port operator; Indonesian National Army (TNI)
5	The port operators decided to continue suspending operations at the Port of Pantoloan due to subsequent aftershocks from the earthquake (L1).	30-Sep-18					√		Port operator
6	The port operators halted the operations for commercial services as the Ministry of Transportation announced that the port would serve as a humanitarian aid hub (for both logistics and refugee transfer) for earthquake and tsunami victims in Central Sulawesi (L1)	01-Oct-18					√		Port operator; Regulatory agency (MOT)
7	The port operator reopened Port of Pantoloan exclusively for humanitarian assistance purposes, temporarily suspending its function as a commercial port. This decision was based on the investigation results assessing the infrastructure damages at Port of Pantoloan and direction from the Ministry of Transportation. The port operated during the day and closed during the night (12 hours a day, from 06:00 to 18:00 local time) (L1)	01-Oct-18					√		Port operator

Table 25 continued

No	Resilience interventions and level category	Time taken $[t_d - t_{s1}]$	Category						Actors involved
			Infrastructure adaptation				Process adaptation		
			Repu	Reloc	Repa	Recon	OF	OA	
8	Port operator, along with approval by port authorities, implemented a policy waiving fees for port services specifically related to humanitarian aid purposes for 14 days (L1)	01-Oct-18					√	√	Port operator, port authority
9	The Directorate General of Sea Transportation (MOT) formed a Quick Response Team (QRT) to assist in providing aid for earthquake victims and clearing debris from the storage yard of Port of Pantoloan. The QRT consisted of class I and II patrol boat officers from KSOP Bitung and Tual Marine Bases (L1).	01-Oct-18			√			√	Ministry of Transportation; KSOP Bitung and Tual
10	The military ships (KRI Dr. Suharso-990 and KRI Makassar-590 berthing in Port of Pantoloan as floating hospitals and to distribute aid to disaster victims (L2).	02-Oct-18					√	√	Port operator; Indonesian military
11	The Ministry of Public Works and Housing (Kementerian PUPR) has deployed heavy machinery to clear the road blocked by a landslide leading to Pantoloan Port on the Kebon Kopi road segment (L2).	02-Oct-18			√				Ministry of Public Works and Housing (PUPR)
12	The Directorate General of Sea Transportation (MOT) supplied the telecommunication kit devices using satellite to improve the coordination for restoring the Port of Pantoloan (L1).	03-Oct-18			√				Ministry of Transportation
13	The Port operator announced the incentive policy for reduced transportation tariffs for civilian volunteers to the Port of Pantoloan (L1).	03-Oct-18					√		Port operator
14	The Ministry of Transportation announced that the Port of Makassar has been prepared to accept refugees from Palu or the Port of Pantoloan (L2).	03-Oct-18		√				√	Ministry of Transport; Port operator of Port of Makassar
15	The Ministry of Transportation and the Directorate General of Sea Transportation issued a direction for PT. Pelni to reduce economy class ship ticket prices by a maximum of 20% for routes to and from Pantoloan Port in Palu (L2).	03-Oct-18					√	√	Ministry of Transport; PT. PELNI (state-owned shipping operator)

Table 25 continued

No	Resilience interventions and level category	Time taken $[t_d - t_{s1}]$	Category						Actors involved
			Infrastructure adaptation				Process adaptation		
			Repu	Reloc	Repa	Recon	OF	OA	
16	Port operators, Indonesian military, and port authorities continued to clean and rehabilitate the passenger terminal, repair lighting, fix RTG cranes, and tidy scattered containers in the stacking yard (L1)	05-Oct-18			√			√	Port operator, port authority, and Indonesian military
17	The Ministry of Transportation assigned the head of KSOP Sunda Kelapa to lead the Disaster Emergency Post at the Port of Pantoloan. This was done to improve coordination for the reception and distribution of aid at the port and to coordinate the evacuation of Palu City residents from Port of Pantoloan (L2)	06-Oct-18						√	Ministry of Transport; KSOP Sunda Kelapa
18	The Ministry of Transportation announced that the Port of Toli-Toli also could be used for distributing aid, in addition to the Port of Pantoloan (L2)	06-Oct-18		√				√	The Ministry of Transport; Port Operator (Toli-Toli
19	Port operators received assistance from civilian volunteers for the rehabilitation of the debris found at the stacking yard and other port areas (L1)	07-Oct-18			√			√	Port operators, civilian volunteers
20	Port operators contacted the operators of the Port of Bitung to explore the possibility of relocating a quay crane to replace the damaged one caused by the tsunami (L1)	09-Oct-18		√				√	Port of Pantoloan operator; Port of Bitung operator
21	The Port operator decided to resume commercial operations at the Port of Pantoloan, with operating hours extending from 12 to 24 hours (L1)	12-Oct-18					√		Port operator

Table 26. Resilience intervention during response phase 2 $[t_{f1}, t_{s2}]$. For the intervention category. Repu = Repurposing, Reloc = Relocation, Repa = Reparation, Recon = Reconstruction, OF = Operational Flexibility, OA = Organizational Agility

No	**Resilience interventions and level category**	**Time taken** $[t_{f1} - t_{s2}]$	**Category**						**Actors involved**
			Infrastructure adaptation				**Process adaptation**		
			Repu	**Reloc**	**Repa**	**Recon**	**OF**	**OA**	
1	The Port operator successfully evacuated the collapsed quay crane at the Port of Pantoloan. (L1)	20-Oct-18			√				Port operator
2	The Port of Pantoloan operator contacted the Port of Bitung to initiate the possibility of relocating the quay crane from Bitung to Pantoloan. (L1)	28-Oct-18		√				√	Port operator (Pantoloan and Bitung)
3	The port operator granted permission for the RSA Nusa Waluya II to dock for one month to aid in the recovery of the communities' health conditions.	12-Nov-18					√		Port operator; RSA Nusa Waluya
4	Port operator decided to invest in more Reach Stacker and equipment handling for the Port of Pantoloan. (L1)	30-Dec-18				√	√		Port operators
5	The port operator announced that the replacement crane from Bitung arrived at the Port of Pantoloan on Sunday, transported by a large barge vessel. (L1)	20-Jan-19		√				√	Operator of the Port of Pantoloan; Operator of the Port of Bitung
6	The port operator announced to the media and public that the replacement quay crane from Bitung has arrived and has been installed at the Port of Pantoloan. However, the replacement quay crane has not been able to function due to the discovery of several damaged components during transportation. (L1)	29-Jan-19		√			√		Port operator Pelabuhan Pantoloan; Port Operator Pelabuhan Bitung
7	The port operator called specialized experts and technicians to inspect and repair the newly arrived replacement quay crane. (L1)	02-Feb-19			√				Operator of the Port of Pantoloan
8	The operator of the Port of Pantoloan announced through official information channels and mass media that the replacement quay crane had been repaired and reinstalled. (L1)	14-Feb-19			√				Operator of the Port of Pantoloan

4.4.3 Resilience Intervention Analysis During Recovery Phase [t_s, t_f]

This subsection discusses the resilience interventions initiated by the operators of the Port of Pantoloan during the recovery phase. This phase spans from when the Port of Pantoloan's loading and unloading capacity returned to its original state, marked by the arrival of a new quay crane from the Port of Bitung on February 13, 2019, until the vessel arrival capacity at the Port of Pantoloan matched its pre-disaster condition on July 21, 2019. What is meant by the recovery phase here is not the recovery of the port container handling capacity but the recovery of port performance represented by container vessel count (CVC).

During this phase, there were no specific efforts to restore shipping services beyond using mass media channels to publicize that the Port of Pantoloan was fully operational again for container ship loading and unloading. This outreach was actively conducted from February 14 to June 2019 to revive trade flow in Palu City and other parts of Central Sulawesi. In February 2019, even when the port had returned to its original capacity, the demand for shipping did not immediately increase. This was because many disaster victims in Palu were still recovering their businesses and slowly increasing their purchasing power. Various factors contributed to this, including the loss of many jobs, the trauma many residents experienced due to the earthquake, and the decision by many to temporarily or permanently evacuate. By July 21, 2019, the traffic of container ships began to return to pre-disaster levels, attributed to the recovering economic conditions and purchasing power of the residents in Palu City.

4.4.4 Resilience Intervention Analysis During the Adaptation Phase ($t > t_f$)

This subsection discusses resilience interventions after the traffic at Pantoloan Port returned to its pre-disaster condition. The intervention in this section focuses on strengthening and preparing the Port of Pantoloan to deal with future earthquake and tsunami disasters. To prepare the port for better preparation, the Government of the Republic of Indonesia, through the Ministry of Transportation, requested the Asian Development Bank (ADB) to finance the Emergency Assistance for Rehabilitation and Reconstruction (EARR) project in Palu. In early August 2019, the government received a foreign loan commitment from ADB amounting to US$ 45 million for the EARR project to rehabilitate, reconstruct, and enhance the Port of Pantoloan.

The scope of work assigned to the Port of Pantoloan from this loan includes improvements to wharves, approach trestles, pavements, buildings (strengthening structures for port administration offices and warehouses to earthquake-resistant levels), lighting, control and communication systems, water, wastewater treatment, power systems, and cargo handling equipment. The EARR project itself is divided into several loan component packages. The Port of Pantoloan rehabilitation project belongs to the component loan for transportation infrastructure with Loan number 3792-INO. After securing the loan from ADB, on September 30, 2021, PT Amarta Karya - Setia Mulia Abadi signed a contract as the EPC contractor for the Port of Pantoloan to work on the following Civil Works package:

- **Main infrastructure facility – offshore**: Work package of 188 x 30 m jetty segment 1 rehabilitation, 11 x 20 m upper structure segment 1 jetty extension, 50 m^2 trestle 1 rehabilitation. The jetty rehabilitation utilizes tsunami-resistant structures, including seismic detailing provisions, progressive collapse prevention measures, and deeper foundation systems.
- **Supporting infrastructure facilities – onshore:** KSOP's office of 1,500 m^2, office parking area, 2 (two) units office house of 80 m^2 per each unit, pump and generator houses, drainage channel of 0.4 x 0.6 x 0.1 m^3, green open space, terminal access road, terminal entrance and exit, and 2 units guard post of 3.5 m x 2.5 m per unit.

The signing of the contract on September 30, 2021 started the physical reconstruction work process at the Port of Pantoloan. The construction process of the port facilities, as mentioned above, was planned to last for ten months.

4.5 Lessons Learned from Empirical Findings

This section discusses the lessons learned after analyzing port resilience over the four phases. The discussion of lessons learned will be divided into three subsections based on the resilience attributes in a resilience cycle. In subsection 4.5.1, lessons learned will be related to the port robustness or vulnerability attributes, which show the ability of the Port of Pantoloan to maintain its performance after a disruption. Subsection 4.5.2, lessons learned will relate to port responsiveness, which describes how responsive port actors were in preparing or gathering resources for starting port performance recovery. Subsection 4.5.3 will discuss lessons learned about port rapidity and recoverability, representing the port's ability to bounce back to an acceptable performance. Lessons learned in this section are expected to help the Port of Pantoloan and other similar ports face earthquake and tsunami disasters in the future.

4.5.1 Lessons Learned Related to Port Robustness/Vulnerability

This case study showed that the Port of Pantoloan theoretically has a robustness value of 0 TEU/day, equivalent to a vulnerability value of 834 TEUs/day, which indicates that Pantoloan Port lost 834 TEUs/day in terms of capacity, equal to the entire value of the average shipping capacity during normal conditions. This suggests that during the earthquake and tsunami, the Port of Pantoloan could not maintain its performance as measured by the theoretical capacity of ships visiting the port, also known as container vessel capacity (CVC). Nevertheless, there are some lessons to be learned based on the empirical analysis result:

1. The Port of Pantoloan did not allocate a specific budget to design and construct physical infrastructure that can withstand earthquakes and tsunamis because these structures are very expensive, and there is also an unknown return on investment when deciding to build these structures. However, the empirical case study results found that the earthquake and tsunami that struck the Port of Pantoloan resulted in the loss of 100% of its commercial traffic for 14 days and around 70% for 125 days. This can be used as a basis for estimating the revenue loss of the port when affected by the earthquake and tsunami. In addition to

the impact of revenue loss, the post-earthquake rehabilitation, reconstruction, and infrastructure strengthening process for the Port of Pantoloan cost around US$45 million. The combined revenue loss plus the costs incurred for reconstruction can be used as a basis for decision-making to invest in strengthening the port's structures to withstand future earthquakes and tsunamis.

2. Due to the limited budget available to develop earthquake and tsunami-resistant building structures, the Port of Pantoloan instead focused on improving the quality of human resources in preparing for earthquake and tsunami disasters. Improving the quality of human resources was done by collaborating with other parties who carry a lot of expertise. In this case, help was offered by the Meteorological, Climatological, and Geophysical Agency (BMKG) to help predict extreme weather and climate change and the Indonesian Institute of Sciences (LIPI), which explicitly researches earthquakes on earthquake faults in the South Sulawesi area. This quality improvement effort can be seen, among others, from the intensity of training provided to port authority officers and port operators in reading tsunami signs and how to respond to them. This training contributed to avoiding casualties among port authority officers and port operator employees during the disaster. In addition, port authority officers could remain on standby to respond and coordinate various parties to assist in post-earthquake recovery at the Port of Pantoloan.

Based on the empirical findings, the Port of Pantoloan can implement the following suggestions to increase robustness or reduce vulnerability to earthquake and tsunami disasters:

1. Prioritize enhancements to physical infrastructure that are critical to resist earthquakes and tsunamis. Based on the results of the disaster impact analysis, it is known that the technical port infrastructure components that are most severely affected by the earthquake and tsunami disaster are:
   a. **Berths** that are at risk of becoming inoperable by debris or stranded vessels caused by tsunamis,
   b. **Quay crane** for loading and unloading containers that may collapse and fall into the water,
   c. **Cargo handling equipment**, such as forklifts and reach stackers, have a high risk of being blown away by a tsunami and, therefore, become unusable.

Knowing these three components are the most affected, the Port of Pantoloan and other similar ports can identify the physical infrastructure or technical components that need strengthening. In this case study, the berth is the most prioritized component because the malfunctioning of the berth will hamper the flow of ship traffic. Examples of efforts to strengthen the berth in the future for the Port of Pantoloan are by making the berth more tsunami resistant, i.e., by using deeper building foundations, using debris deflection booms, increasing the size and stability of dock piles, raising the height of piles to prevent overtopping, constructing breakwater barriers farther away from the harbor, and fortifying and armoring the breakwater barriers. These examples of interventions are expected to maintain the residual capacity of container loading and unloading within a certain value so that the port can continue to run even when affected by disasters, ultimately increasing port robustness and reducing port vulnerability.

2. Proactively seek other funding sources to strengthen port structures that are stronger and more resistant to earthquakes or tsunamis. Funding from the state budget (APBN) or local government budget (APBD) is generally limited to developing structures that exceed the normal specifications required for earthquake and tsunami resistance. Several other types of funding can be done, such as cooperating with Regional Government Owned Enterprises (BUMD), cooperating with domestic and foreign investors to conduct public-private partnerships, issuing debt securities, or making foreign loans.

4.5.2 Lessons Learned Related to the Port Responsiveness

In the case of the Port of Pantoloan, the response phase was divided into two parts, both of which showcase the port's ability to address disaster impacts. In response phase 1, the empirical analysis found that the Port of Pantoloan's responsiveness was 13 days. This 13-day duration indicates the time taken from the total closure of the Port of Pantoloan to its reopening for commercial container vessels. Meanwhile, response phase 2 lasted 125 days, starting from the port's reopening for commercial operations until its capacity returned to normal with the arrival of a replacement quay crane. The following are some lessons learned based on the results of the empirical analysis in response phase 1:

1. For disasters that occur on a large scale with a wide impact, this case study shows that the decision of a 13-day disaster emergency status needs to be based on a multi-actor agreement to create integrated disaster management between actors and agencies in Central Sulawesi. The implementation of the 13-day emergency disaster status was based on coordination from the local government based on field conditions in Palu, Donggala and Sigi, which also provided a report to the Governor of Central Sulawesi so that a Decree (SK) of the Governor of Central Sulawesi Number 466/425/BPD/2018 was issued which one of the mandates is to establish the Port of Pantoloan to become a hub for the distribution of humanitarian assistance. Based on this mandate, the port closed all services for commercial shipping and only served humanitarian vessels. During the disaster emergency, port operators assessed and prioritized the repair of affected infrastructure and gathered the required materials, budget, and human resources to carry out initial repairs.

2. With the implementation of the collective disaster emergency period, disaster management collaboration between agencies became easier and faster. This can be seen from the rapid collaboration between the operator of the Port of Pantoloan, KSOP Class III Teluk Palu as port authority, the Indonesian National Army, State-Owned Shipping Companies, and other related agencies to prepare the resources needed to rehabilitate the port. The result was the reopening of the inoperable berth, which was not functioning because it was covered by tsunami debris and stranded ships within two days after the disaster and on the third day, it

was able to receive humanitarian aid ships and become a hub for moving refugees from the Port of Pantoloan to other cities.

3. The operational flexibility[14] of the Port of Pantoloan in response phase 1 showed an effective strategy to rehabilitate the capacity of Pantoloan Port in loading and unloading cargo while helping the recovery of local communities who were victims of the earthquake in Central Sulawesi. With the establishment of the Port of Pantoloan as a hub for the entry of humanitarian aid, the rehabilitation of critical physical infrastructure such as berths and access roads was prioritized for immediate repair. However, as a trade-off, the Port of Pantoloan had first to delay receiving commercial vessels, which resulted in a considerable loss of potential revenue. The role of the port as the hub for humanitarian aid made this port very busy receiving humanitarian aid from October 1 to 10, 2018.

4. The disaster emergency status imposed by the Port of Pantoloan significantly impacted shipping network connectivity on Sulawesi Island. Based on the results of the empirical analysis, commercial ships scheduled to Pantoloan switched to alternative ports that met three conditions: sufficient spare capacity, shorter or equal travel distance, and hinterland access to the Pantoloan or Central Sulawesi region. Implementing the emergency status made ships from western Indonesia divert to the Port of Makassar, while ships from eastern Indonesia went to the Port of Kendari as an alternative for loading and unloading containers. The existence of these alternative ports has proven to be very important because it can be a buffer for traffic on Sulawesi Island, where even though the Port of Pantoloan is under emergency status, the capacity of freight shipping serving Sulawesi Island only decreased by a relatively small 2%.

5. The level of accessibility of the transportation network (in this case study, roads) can empirically be a trigger to accelerate or hinder the resilience of the Port of Pantoloan. As evidence, in the aftermath of the disaster, many critical road sections connecting Pantoloan port with alternative ports in northern Sulawesi and southern Sulawesi were unusable due to cracks or landslides. This meant that the alternative port could not effectively mobilize human resources, materials, and equipment that could be used to repair the Port of Pantoloan. In addition, with the inaccessibility of the road, commercial shipping services bound for the Port of Pantoloan were canceled as they could not use alternative ports for rerouting. At the same time, the Port's berths could not be used for loading and unloading cargo. However, this issue was resolved with the cooperation of the Indonesian National Army and the National Disaster Management Agency (BNPB) who helped to clear debris and evacuate shipwrecks stranded at the berth so that within three days of the disaster, all human resources, materials, and equipment for port repairs and victims of the Palu earthquake could be sent directly to the Port of Pantoloan. When the road connecting the Port of Pantoloan with the Port of Makassar and Kendari opened on October 3, the flow of

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[14] What is meant by operational flexibility is the shift in the main function of the Port of Pantoloan from a commercial entity to a port for humanitarian aid hub for earthquake victims in Palu, Central Sulawesi.

humanitarian aid goods for Central Sulawesi Province, as well as the mobilization of material resources, volunteers, and equipment needed to repair the Port of Pantoloan could be increased.

Response phase 2 continued after response phase 1 was completed, which began on October 12, 2018 when the Port of Pantoloan could reopen its services to commercial vessels with limited loading and unloading capacity. The end of response phase 2 was February 14, 2019 when the port's capacity had returned to normal. Port responsiveness in response phase 2 took approximately 125 days. Concerning response phase 2, the following are some of the lessons learned:

1. When reopened with limited capacity, the Port of Pantoloan could only serve commercial shipping with a loading and unloading capability of 30% of its initial performance. The limited capacity was due to a collapsed quay crane, and the Pantoloan port relied only on cranes found on container ships. This caused congestion that made many large container ships reroute to alternative bigger ports such as Makassar and Kendari, and some at ports in East Kalimantan. In terms of Pantoloan Port as a business entity, this rerouting was a traffic loss because there was no agreement or cooperation agreement from the beginning to capture the lost traffic with other alternative ports on Sulawesi Island, and the number of ships rerouting could not be claimed as cargo entering Pantoloan Port. This condition lasted for 125 days. However, regarding the network level and resilience of Sulawesi Island, these alternative ports are important to prevent Sulawesi Island from becoming isolated and keep the goods and services flowing smoothly. This situation demonstrates the evident trade-off: alternative ports are good for maintaining island community resilience but can cause the affected ports to lose a lot of traffic if there is no cooperation agreement from before the disaster.

2. Relocating quay cranes from other ports can be a quick response measure to restore lost loading capacity, especially when a port has a limited rehabilitation budget but is pressured to quickly restore available loading capacity. However, ports should anticipate the complexities of such relocation in archipelagic regions. By the end of November, there was an initiative to move a quay crane from the Port of Bitung, several hundred kilometers from Pantoloan Port and also located on Sulawesi Island. However, most of Sulawesi's flat roads have limited capacity, while others are hilly or mountainous, making it impossible to transport the crane overland even within the same island. This added complexity to the relocation efforts, as the only feasible route was by short sea shipping. The total duration from planning to executing this crane relocation through sea transport took approximately two months.

3. Based on the empirical findings related to the port responsiveness of the Port of Pantoloan described above, here are some things that can be done as recommendations to improve port responsiveness for the Port of Pantoloan or other similar ports. This timeframe doesn't include the loading, unloading, and installation processes at the Port of Pantoloan, which

took another nine days. During testing, damages were found on the quay crane, rendering it unusable immediately upon installation at the Port of Pantoloan. Most of these damages resulted from mishandling during transport. Repair and testing showed that fixing these issues required an additional 14 days. Transferring the crane from Bitung until it is ready for use at the Port of Pantoloan takes about 31 days.

Based on the empirical findings related to the port responsiveness of the Port of Pantoloan described above, here are some things that can be done as recommendations to improve port responsiveness for the Port of Pantoloan and other similar ports:

1. Increase the number of alternative access roads that can be traversed by trailer trucks for 20 and 40 TEU containers, especially those connecting the Port of Pantoloan with other container ports that have sufficient spare capacities that can mobilize resources for restoring Port of Pantoloan in addition to preventing traffic loss for commercial shipping customers. There are currently two main roads connecting the Port of Pantoloan with container ports in North Sulawesi, two routes connecting Pantoloan with the Port of Makassar in South Sulawesi, and one route connecting Pantoloan with the Port of Kendari in West Sulawesi. The relatively small number of routes means that access to the Port of Pantoloan is at risk of being completely closed if these routes are affected by a disaster.

2. Prepare a cooperation procedure on diverting commercial container ships that cannot berth at the Port of Pantoloan to alternative container ports on Sulawesi Island. This cooperation can be in the form of determining a mutually beneficial business model between the two parties. Thus, even though the Port of Pantoloan cannot serve container loading and unloading, it does not lose traffic that switches to other ports. The opposite can also be done if the alternative port experiences a disaster, then, the Port of Pantoloan can be prepared as a buffer port to accommodate traffic from the alternative port, benefiting both parties from a business perspective.

3. Prepare a hinterland fleet to capture container ships that divert or reroute to other alternative ports on Sulawesi Island. For the Pantoloan Port case study, the 1 TEU truck fleet in Central Sulawesi in 2021 amounted to 763 trailer trucks (BPS, 2023). Assuming that Pantoloan Port can coordinate and cooperate with the truck fleet in Central Sulawesi, this number can be adjusted according to the analysis we have done in Table 19. This can accelerate the recapturing of container traffic that switches to alternative ports on the island of Sulawesi.

4. The Port of Pantoloan and alternative ports on Sulawesi Island should consider investing in mobile harbor cranes for container loading and unloading. Mobile harbor cranes are cranes that can be mobilized more easily and can be adapted to the road conditions on Sulawesi Island. By investing in mobile harbor cranes, container ports can work together to back up each other's capacity for container handling by mobilizing mobile harbor cranes if one or more ports are affected by a disaster.

4.5.3 Lessons Learned Related to Port Rapidity/Recoverability

In this case study, the Port of Pantoloan had a port rapidity value of 157 days and port recoverability of 3 TEUs per day. Port rapidity and port recoverability indicate how quickly port performance, measured by container vessel capacity (CVC), returns to its original condition after the port's container handling capacity has recovered to its previous state. Based on the results of the empirical analysis, the following are some lessons learned that can be taken related to port rapidity or port recoverability:

1. The recovery of port performance does not always directly follow the recovery of container handling capacity carried out by the port. The empirical analysis that was carried out found that it took about five months for the Port of Pantoloan to recover port performance as measured by container vessel capacity (CVC) visiting the port after the loading and unloading capacity returned to normal.

2. The recovery of performance indicators, which took five months, was due to several factors. The first factor is that some vessels avoided congestion at the Port of Pantoloan by berthing at the Ports of Makassar and Kendari. Some shipping services with fixed schedules are known to be bound by service route agreements, and they are waiting for these contracts to expire before moving back to the Port of Pantoloan. The second factor is the stagnant demand in Central Sulawesi, where economic conditions and purchasing power have not fully recovered. Demand in Central Sulawesi from early 2019 until mid-year still revolved around construction materials and tools for building repairs and reconstruction, so few commercial vessels were interested in visiting the Port of Pantoloan. One of the crucial lessons in this recovery phase is that even if a port's capacity has been quickly restored to its original state, maritime transport demand depends on purchasing power, market demand, or the economic condition of the island. These factors may not always recover as quickly as the port's capacity improvements.

Based on the empirical findings related to port rapidity and port recoverability of Pantoloan Port that have been described above, the following are some things that can be considered as recommendations to improve port rapidity and recoverability of the Port of Pantoloan or other similar ports:

1. Increase awareness among commercial shippers and shipping companies related to the condition of the Port of Pantoloan after the container handling capacity has returned to normal. This informs vessels anchored at alternative ports to return to berthing at Pantoloan, especially when delivering cargo for Central Sulawesi province. Several communication channels can be used, such as one-way channels such as official websites, mobile applications, and mass media, or two-way communication channels such as social media.

2. Cooperate with the government and stakeholders in the hinterland to accelerate economic growth. For example, state-owned companies on the island of Sulawesi can be required to

procure goods from small and medium enterprises in Sulawesi to increase port traffic in the Sulawesi region. In addition, cooperation can also be provided in the form of tariff reduction on transportation and logistics costs related to the entry and exit of goods in Central Sulawesi so that goods can be accessed more quickly and efficiently by the community so that people's purchasing power will be improved more quickly and the vessel traffic will rise again.

4.6 Concluding Remarks and Summary

Chapter 4 describes the implementation of the method to evaluate port resilience in an archipelago setting, namely the Port of Pantoloan in Central Sulawesi, Indonesia, and the results of the empirical analysis. On September 28, 2018, Pantoloan Port was affected by a 7.5 Mw earthquake and tsunami. This chapter demonstrates how to apply the four phases of port resilience evaluation, and it presents the analysis results for each phase.

Section 4.1 describes the implementation of phase one, the port system, and island connectivity analysis. This section discusses in detail how the port system at Pantoloan Port from a socio-technical system perspective is depicted in a diagram in Figure 22. This section also describes the connectivity condition of transportation infrastructure in Sulawesi Island from the perspective of complex network analysis, where the aggregate shipping connectivity of Sulawesi Island is shown in Table 13, and the port-hinterland network condition is shown in Figure 23. The analysis results in section 4.1 are useful for knowing the context of the analysis and making it easier for readers to identify other ports with similar port and island conditions.

Section 4.2 describes the implementation of phase two, the resilience curve analysis. The resilience curve in one resilience cycle is constructed based on a single performance indicator, the Container Vessel Capacity (CVC) for port visits. Based on the construction of the resilience curve shown in Figure 27, theoretical resilience attributes such as port robustness, vulnerability, responsiveness, rapidity, and recoverability of Pantoloan Port when facing earthquakes and tsunamis can be calculated more precisely. Based on the results of empirical analysis, the value of port robustness is 0 TEU/day; port vulnerability is 834 TEU/day (loss of all daily capacity of container ships visiting Pantoloan Port); port responsiveness in total is 139 days; port rapidity is 157 days; and recoverability is 3 TEUs per day.

Section 4.3 describes the implementation of phase three, the disaster impact analysis. This section focuses on explaining the direct and indirect impacts of the disaster on the Port of Pantoloan and the connectivity of the transportation network on Sulawesi Island. The direct impact of the disaster on the technical components of the Port of Pantoloan was the closure of the berths with tsunami debris and stranded ships, the collapse of the quay crane for loading and unloading containers, and the malfunctioning of some container handling equipment. Meanwhile, access roads connecting Pantoloan Port with ports in northern Sulawesi, such as Toli-Toli, Anggrek, Bitung, and Gorontalo Ports, were covered by landslides. The road network connecting ports in the southern part of Sulawesi, such as the ports of Makassar and Pare-Pare, suffered cracks due to the earthquake and liquefaction. The closure of the Pantoloan port also impacted the decrease in container vessel capacity connected to Sulawesi Island by 1-2% compared to normal conditions.

Section 4.4 describes the implementation of phase four, the resilience intervention analysis. The analysis in this section focuses on identifying the interventions taken by port stakeholders in each phase of the resilience cycle. In the preparation phase, the operators of the Port of Pantoloan focused more on strengthening the organization and human resource capacity in responding to disasters than preparations for the port's technical aspects or physical infrastructure. In response phase 1, the Port of Pantoloan focused on shifting its function as a humanitarian aid hub rather than functioning as a commercial entity and completely shut down services for commercial container ships as a follow-up to the mandated disaster emergency status in Central Sulawesi province. Then, in response phase 2, the Port of Pantoloan reopened services for commercial vessels, although it only had 30% loading and unloading capacity. In this phase, the Port of Pantoloan operator moved the quay crane at the Port of Bitung in North Sulawesi to Pantoloan by sea or through short sea shipping. For the recovery phase, the Port of Pantoloan operator focused on communicating the condition of the recovered container handling capacity of the Port of Pantoloan repair to the public, including shipping companies and communities, especially in the Central Sulawesi region.

Section 4.5 summarizes the lessons learned based on the empirical analysis and its relationship to theoretical resilience attributes. The lessons learned in this section are the results of the empirical analysis that can be considered to explain what causes the values of the resilience attributes described in Section 4.2. The explanation in section 4.5 is followed by recommendations that the port’s stakeholders can adopt to improve resilience attributes in the future.

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5 Case Study: Port of Seba

Chapter 5 is the second chapter that shows the application of the empirical evaluation methods for resilience in island regions. This chapter tests the evaluation approach at the Port of Seba in the East Nusa Tenggara Province during Tropical Cyclone Seroja, specifically from April 3 to April 12, 2021[15]. To understand the context of the tropical cyclone disaster, please refer to subsection 3.3.2.

This chapter is divided into six sections corresponding to the phases of the empirical port resilience evaluation method. Section 5.1 explores the application of the first phase of the evaluation method by examining the Port of Seba as a socio-technical system at the Port Level and by studying Sabu Island's transport connectivity as a complex spatial network to understand the case study context. Section 5.2 discusses the empirical resilience curve analysis based on selected key performance indicators relevant to the Port of Seba. Section 5.3 provides a detailed analysis of the impact of Tropical Cyclone Seroja on the Port of Seba and Sabu Island's connectivity. Section 5.4 explores interventions and strategies at the port level (L1) and island transportation network connectivity level (L2) within a resilience cycle consisting of four phases: preparation, response, recovery, and adaptation. Section 5.5 presents the synthesis and lessons learned from the empirical findings and how they relate to the theoretical resilience attributes. This section also provides some recommendations to port stakeholders to improve the theoretical resilience attributes based on the findings of the empirical analysis. Finally, Section 5.6 summarizes the empirical port resilience evaluation findings to conclude this chapter.

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[15] The datasets used in this case study are available at https://doi.org/10.4121/79b87757-2af5-4a12-a012-afc936a731e0

5.1 Phase 1: Port System and Island Connectivity Analysis

Section 5.1 is divided into three parts. Each part focuses on a different aspect of the analysis to understand the context of this case study. Subsection 5.1.1 examines the Port of Seba as a socio-technical system by identifying and analyzing its operation's technical and social components and linkages. In subsection 5.1.2, the analysis will focus on the connectivity of Sabu Island's port-hinterland network using metrics we adapted from graph theory. In Section 5.1.3, the study will focus on the connectivity analysis of sea shipping connected to Sabu Island using metrics formulated from complex network analysis.

5.1.1 Analysis of Port of Seba and Its Operations as a Socio-Technical System

This subsection describes the technical and social components of Seba Port, along with the linkages between them. This subsection explores the case study context at the port level, highlighting characteristics distinguishing it from the sample ports in other case studies. We begin this section by describing the Port of Seba with a brief overview of its condition in 2021 before it was affected by Tropical Cyclone Seroja. Next, using the block diagram, we conceptualize the port as a socio-technical system, describing all the components involved in its operation and their interrelationships.

Overview of the Port of Seba

Sabu Island is a small island with an area of only 421.4 km^2. In 2021, the total population of Sabu Island was 103,745 people (Sabu Regency Government, 2022). Sabu Island is part of Sabu Raijua Regency. Sabu Raijua Regency lies south of East Nusa Tenggara. The Port of Seba, the Port of Biu, and the Port of Raijua, are crucial for the remote and outer islands of Sabu and Raijua, serving as the main entry and exit points. The Port of Seba, located in the West Sabu sub-district, covers a land area of 25,961 square meters and a water area of 1,384,199 square meters. It is situated on Sabu Island, as depicted in Figure 35. The Seba Class III Port Operator Unit (KUPP Kelas III Pelabuhan Seba), under the supervision of the Ministry of Transportation of Indonesia, manages all three ports in the Sabu Raijua Regency.

The Port of Seba is a non-commercial port that aims to enhance connectivity for Sabu Island, one of Indonesia's most minor and isolated islands. The shipping routes serving these remote islands have minimal economic value. As a result, passenger and cargo transportation relies on multipurpose vessels and non-commercial public ports that receive government subsidies as part of their obligation to improve connectivity in these remote areas. The Port of Seba primarily handles various types of cargo, such as rice, cement, corn, fertilizer, and asphalt. The Port of Seba predominantly handles non-containerized goods, including general and bagged cargo. According to the data from the Central Bureau of Statistics, Republic of Indonesia (BPS, 2021), under normal conditions, the receiving cargo ship capacity per day for the Port of Seba is on average 1,448 DWT.

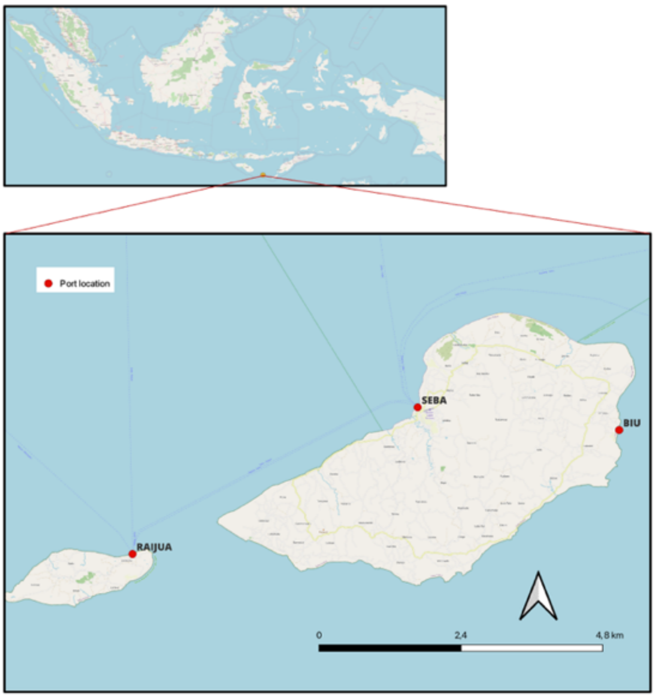

Figure 35. The location of the Port of Seba on Sabu Island, Sabu Raijua District, East Nusa Tenggara Province (Adapted from Open Street Map)

The Port of Seba has been classified as a Collector Port by the government of Indonesia since 2017, based on specific criteria. These criteria include being close to national shipping routes, being at least 50 nautical miles away from other collecting ports, having a dock channel depth of 7-9 meters below low sea level, having a pier with a maximum capacity of 3,000 Deadweight Tons (DWT), and having a pier length ranging from 120 to 350 meters. Collector ports focus on regional connectivity and support the transfer of passengers and goods with neighboring ports. These ports' functions differ from those of a main port, facilitating large-scale international and domestic trade. Figure 36 shows the situation of the Port of Seba before it was affected by Tropical Cyclone Seroja.

Figure 36. View of the Port of Seba in East Nusa Tenggara, Indonesia (Courtesy of Ministry of Transportation, 2019)

The layout of the Port of Seba in 2019 (before the Seroja tropical cyclone event) can be seen in Figure 37. At that time, the Port of Seba had two types of docks. The first is a general berth of 90 meters, mainly used for loading and unloading general cargo vessels and bagged cargo. This berth is connected to a 110-meter-long trestle. The second is dedicated to roll-on/roll-off (ro-ro) vessels and is 37 meters long. This ro-ro berth is also connected to a 110-meter-long trestle. Table 27 describes the physical facilities at the Port of Seba in 2021. In addition to technical facilities, Table 28 presents a list of social components and port actors at the Port of Seba. The list of social components in the table is limited to the first layer actors defined by UNCTAD (2020). First-layer actors are social components with a significant role and authority in port operations, including implementing strategies to increase port resilience.

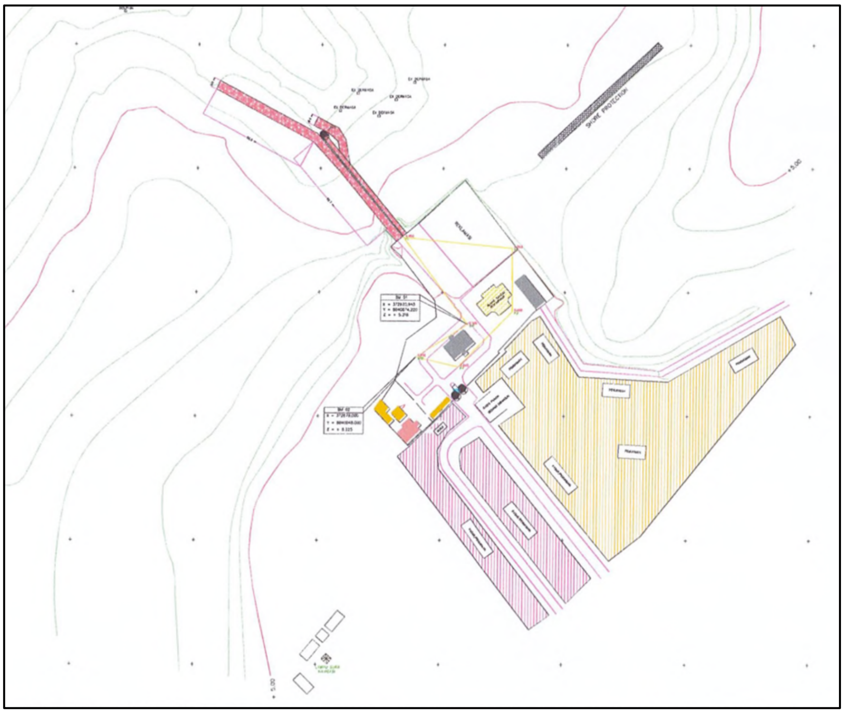

Figure 37. The layout of Port of Seba (Courtesy of Ministry of Transportation, 2019)

Table 27. Existing facilities of Port of Seba in 2021

No	Facilities	Units	Dimension
1	General berth	m^2	90 x 8 = 720
2	Ro-ro berth	m^2	37 x 8 = 293
3	Trestle to general berth	m^2	110 x 6 = 660
4	Trestle to Ro-Ro ramp	m^2	110 x 3.5 = 385
5	Reclamation land	m^2	80 x 43 = 3,400
6	Warehouse	m^2	20 x 10 = 200
7	Passenger terminal 1	m^2	20 x 10 = 200
8	Passenger terminal 2 (new)	m^2	25 x 19 = 475
9	Office UPP	m^2	12 x 8 = 96
10	KPLP Post	m^2	9 x 5 = 45
11	Employee house	Unit	3
12	Prayer room	m^2	6 x 6 = 36
13	Gate in / out	m^2	1

Table 28. A list of first-layer actors (social components) that support the operational aspects of the Port of Seba

Actors	Entities	Roles	Personnel
Port Authority	The Seba Class III Port Operator Unit (UPP Class III Seba)	Harbormaster/port authority officer	4
Port / Terminal operator	The Seba Class III Port Operator Unit (UPP Class III Seba)	Maritime traffic and transport services officer	2
		Port facility and compliance officer	1
		Administrative officer	6
	Non-formal entities*	Provide stevedoring services	35 - 40 (estimation)

*) "Non-formal entities" means that no formal legal entity currently regulates stevedores working for loading and unloading activities at the Port of Seba. These stevedores are residents around the port who offer their services and are generally managed by a labor coordinator who is an influential person in the local communities.

Port of Seba as a socio-technical system

To illustrate the Port of Seba operations as a socio-technical system, we conducted discussions with two experts from the Transportation Research and Development Agency, Ministry of Transportation Republic of Indonesia (BALITBANGHUB) in October - December 2021. Table 29 provides information about the background of the experts we engaged in the discussion. This discussion was held online. The outbreak of COVID-19 made it difficult for us to visit the Port of Seba. Figure 38 shows the block diagram resulting from the discussion with the experts.

Table 29. The list of experts we consulted to conceptualize Port of Seba as a socio-technical system

Role	Institution	Years of working experience
Head of sea transportation research and development	Ministry of Transportation, Republic of Indonesia	14
Acting manager of research facility for sea and inland waterways transport research	Ministry of Transportation, Republic of Indonesia	12

Figure 38 shows the mapping of each technical and social component at the port level and how they relate to each other in supporting the operation of the Port of Seba. In the port operations block (depicted in part (a) in Figure 38), we categorized four operations at the Port of Seba based on their location. The four categories are ship operations, quay operations, storage yard operations, and inland transport operations. We mapped how these operations' technical and social aspects relate. Below is a more detailed explanation of each operation at the Port of Seba.

First, ship operations describe the arrival and departure of vessels that berth and handle cargo at the Port of Seba. In this part of the operation, ships owned by state-owned enterprises (such as PT. Pelni), which operate with government subsidies to serve shipping to Indonesia's outer islands, generally have a large capacity exceeding 5,000 gross tons (GT). These large vessels cannot dock at the berth and must anchor away from the shore due to the limited draft depth at the Port of Seba. These large ships are assisted by smaller or transfer ships (called *rede transport*) for loading and unloading cargo. This *rede transport* has the role of taking cargo from large ships that are offshore and sailing to the Port of Seba for unloading.

The rede transport also loads goods for outgoing shipment from Sabu Island and transfers them to larger capacity vessels waiting offshore. The technical components important in ship operations are large, small, and transfer vessels. The social components that play an important role in ship operations are the harbormaster, traffic, and sea transportation officers from *Unit Pelayanan Pelabuhan* (UPP) Class III Seba, and ship crew and stevedores. The harbormaster certifies and verifies ship documents before docking at the Port of Seba. Meanwhile, traffic and sea transportation officers are also essential, overseeing the scheduling of ship arrivals and departures at the Port of Seba.

The second part of the operation contains the quay operations, where the goods are loaded and unloaded at the Port of Seba. The arrows on the quay operations indicate the flow of goods to and from the Port of Seba. At this location, general and bagged cargo from *rede transport* is loaded and unloaded by stevedores onto inland trucks or transferred to storage (warehouses) using port stevedoring labor. The berth is also very important for docking ships and loading and unloading to support quay operations. At the Port of Seba, two docks facilitate these activities: a 90-meter-long general dock and a 37-meter-long special dock for Ro-Ro ships.

Social components that support dock operations include port actors who act as supervisors and operators. The supervisory role is carried out by officers from the Seba Class III Port Operator Unit (UPP Class III Seba), with one port facility and compliance officer responsible for overseeing legal compliance of port facilities and infrastructure at the Port of Seba. In addition, two traffic and sea transportation officers supervise the scheduling of ship berthing and the ongoing loading and unloading process. As for loading and unloading activities, it usually requires around 5 to 10 stevedores to handle the loading and unloading of cargo in addition to the crew operating the ship.

In the third category of operations at the Port of Seba, storage yard operations focus on transferring cargo from vessels to storage areas. The storage area at the Port is a 200 m^2 warehouse. The warehouse serves as a temporary transit point for general or bagged cargo from ships before being transferred to inland trucks. Two critical technical components in this operation are the temporary storage warehouse and the trucks responsible for transporting the goods from or to the hinterland.

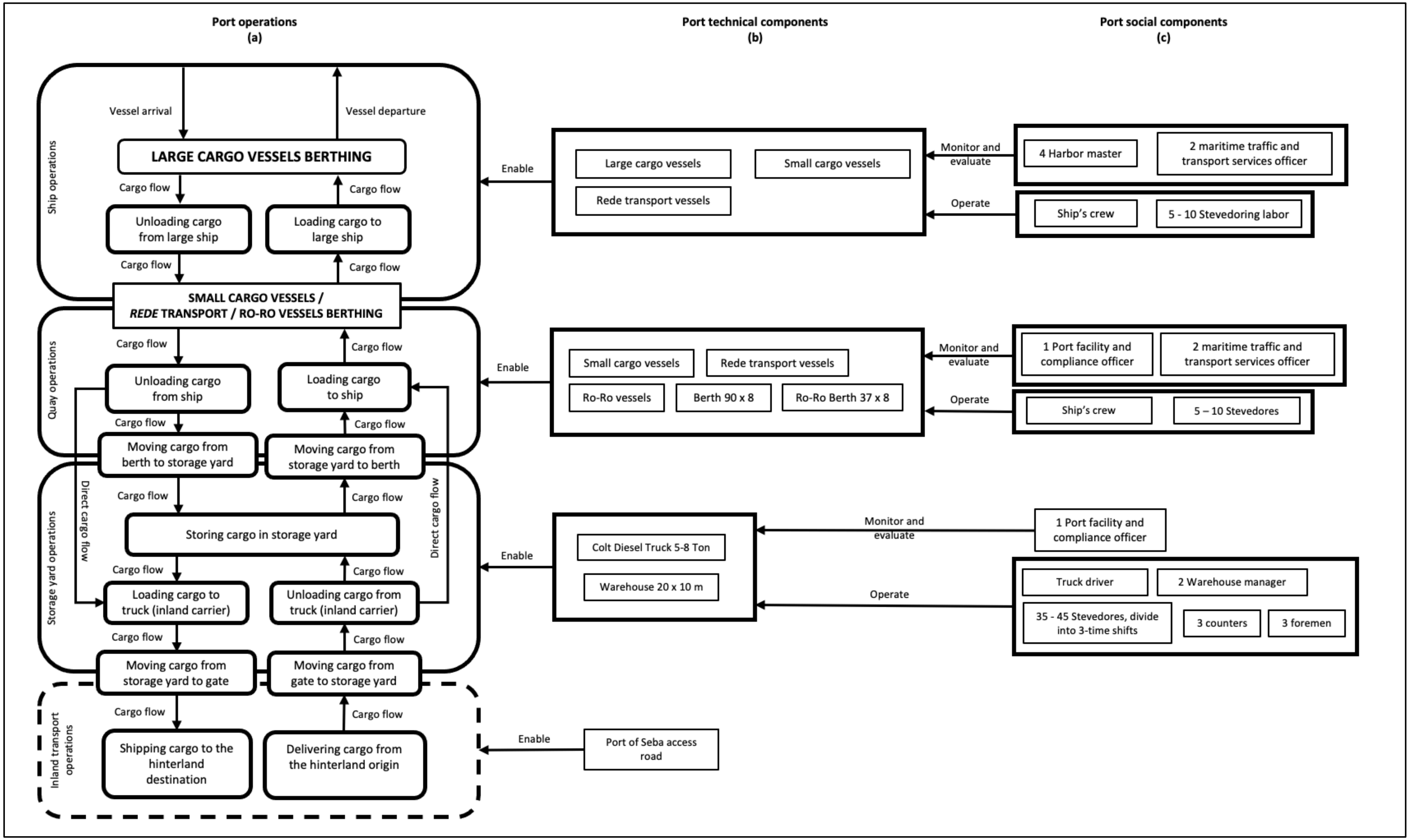

Figure 38. The conceptualization of Port of Seba and its operations as a socio-technical system

There are two schemes for transferring goods from ships to inland trucks. The first is the direct transfer scheme, which is when the truck designated to transport arrives on time. The second scheme is to use the warehouse for transit for the cargo to wait to be transferred to the truck. The transfer of goods from ships to inland trucks is carried out by stevedoring labor due to the limited cargo handling equipment at the Port of Seba. The social components contain 30 to 45 stevedores working 3 shifts a day, truck drivers, warehouse managers, loading and unloading supervisors, and officers responsible for counting the goods moved, also known as counters. The port facility and compliance officer from UPP Class III Seba supervise this operation.

The fourth category of operations is inland transport, which focuses on transporting cargo from the port to destinations in the hinterland. The Port of Seba is connected to two main access roads that facilitate inland transportation and provide access to the port. The first access road connects the Port of Seba with the West Sabu Region and Hawu Mehara Region in the southwestern part of Sabu Island. The second access road connects the Port of Seba to the East Sabu Region and connects the Central Sabu and South Sabu regions. Regarding inland connectivity, there are no alternative transport modes to replace the existing road network on Sabu Island, such as railways or inland waterways. We only focused on first-layer actors since actors in the operations section generally have limited authority to intervene in operations related to hinterland transport or inland trucks.

5.1.2 Analysis of Sabu Island's Ports-Hinterland Network Connectivity

In this subsection, we empirically analyze the condition of the port-hinterland connectivity[16] networks on Sabu Island. The SC_p and $SCRI_p$ metrics developed in Chapter 3 were used in this case study to measure the quality of port-hinterland network connectivity. SC_p is a value that shows the spare capacity available at alternative ports on Sabu Island. Meanwhile, $SCRI_p$ is a value that shows to what extent (in percent) an alternative port can fulfill the capacity needs of the affected port. On Sabu Island, there is only one alternative port besides the Port of Seba, the Port of Biu. However, after we consulted with experts, feedback suggested considering Tardamu Airport as an alternative for loading and unloading cargo. Tardamu Airport is an airport used for inter-island passenger transportation in everyday situations. The suggestion to include this airport was based on the masterplan of Tardamu Airport, which states that the airport is also intended for temporary logistics entrance to Sabu Island in an emergency. Based on the feedback, this section analysis includes Tardamu Port as one of the vertices in the port-hinterland network at Sabu Island.

Two data sources are used to calculate how much spare capacity (SC_p value) is available for each alternative port on Sabu Island. The first data source is the Port of Biu and Tardamu Airport masterplan document obtained from the Ministry of Transportation of the Republic of Indonesia (Ministry of Transportation, 2019; 2022). The masterplan document contained

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[16] In this context, we describe the Port-Hinterland network as a transportation network consisting of vertices (which represent ports) and edges (which represent transportation capacity within the island, either in the form of roads, railways, or inland waterways) that connect one port to another.

sufficient information for calculating the maximum theoretical daily capacity for handling cargo vessels by alternative ports or airports on Sabu Island.

The second data source for this analysis is the 2020 sea transportation statistics published by the Central Bureau of Statistics (BPS, 2021). The sea transportation statistics data shows the realization of the capacity of ships visiting alternative ports at the port for 1 year. The spare capacity per port, SC_p, is obtained by using the theoretical maximum vessel capacity that can be handled daily by the alternative port and subtracting the daily utilization of that capacity at the alternative port. To calculate the $SCRI_p$ value, the SC_p value is then compared with the average daily capacity needed at the Port of Seba in serving cargo ships, which was 1,448 DWT per day in 2020. Table 30 shows the SC_p and $SCRI_p$ calculation results for each alternative port and airport on Sabu Island other than the Port of Seba.

Table 30. The SCRIp value of ports in Sabu Island to replace the lost capacity from the Port of Seba

Other ports on Sabu Island	**Daily Spare Capacity in DWT (*SC_p*)**	**Daily Spare capacity replacement per port (*$SCRI_p$*)**
Biu	535	37%
Tardamu (airport)	200*	13%*
	Total $SCRI_p$	50%

* This figure applies when an emergency period is in effect where Tardamu Airport is open to sending/receiving cargo. During normal operations, Tardamu Airport only provides flight services for passengers. We included Tardamu Airport due to suggestions from the experts we interviewed. Capacity is equivalent to DWT units on cargo ships.

The Port of Biu has only 37% of the capacity of the Port of Seba in case of a complete disruption, according to the data shown in Table 30. At the same time, 13% of the capacity can be diverted to Tardamu Airport. The alternative ports on Sabu Island only have a total spare capacity of 50% of the capacity required by the Port of Seba to serve cargo ships' daily loading and unloading demand. This empirical analysis shows that if the Port of Seba experiences a total disruption, Sabu Island could potentially lose 50% of the outbound/inbound cargo traffic.

The following analysis stage focuses on the edges of the port-hinterland network in Sabu Island. This analysis aims to understand how accessible the Port of Seba is from alternative ports on the island. This ease of accessibility is expressed by $N_p(t)$[17] with the calculation formula in Equation (4). In this case study, the calculation of $N_p(t)$ is limited to cargo trucks with a carrying capacity of 12 tons, as shown in Figure 39. These trucks usually have a tub size of 6 meters long, 2.45 meters wide, and 1.8 meters high. The goods from ships are typically loaded on this truck using an open tub covered by plastic. This type of truck is the only inland transport mode to mobilize cargo from the port to the hinterland of Sabu Island. Using this truck model specification, the value of dt_p[18] can be calculated as a condition to obtain the value of $N_p(t)$.

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[17] $N_p(t)$ is "*the number of inland transport resources required per day to utilize the spare capacity of alternative ports at the given time t under normal conditions.*"

[18] dt_p is the shortest time spent on a round trip from alternative port p to disrupted port d taken by the hinterland transportation mode (in this case study, trucks with a carrying capacity of 12 tons).

Figure 39. Photo of a 12-ton truck commonly found on Sabu Island (courtesy of Ministry of Transportation, 2022)

The value of dt_p can be calculated if all the road sections connecting the alternative port with the disrupted port can be identified. The dt_p value is taken from the shortest round-trip time among all available road options. We use data from the Indonesian National Geospatial Information Agency (BIG, 2022) to identify all roads connecting ports on Sabu Island. With this information, we calculated the travel time required by the 12-ton truck on each road from the alternative port p to the disrupted port d (one-way trip). The spatial distribution of roads connecting ports on Sabu Island is shown in Figure 40. We did consider the type of road elevation (whether flat or hilly) affecting the truck's speed. In calculating the one-way trip, we have also considered the time required for truck drivers to rest. Table 31 shows various alternative road segments that connect the Port of Seba with alternative ports in Sabu Island, along with the road segment name, terrain type, distance (in kilometers), and travel time required for a one-way trip.

Table 31. List of roads connecting the Port of Seba to other ports on Sabu Island

Origin - Destination	Road segment name	Terrain / Type	Distance (km)	Average *one-way* Travel Time (Min)*
Seba - Biu	Jl. Trans Seba Bolou (Route 1)	Asphalt flat road	27.2	80
Seba - Biu	Jl. Masjid An-Nur Seba (Route 2)	Asphalt flat road	26	130
Seba - Biu	Jl. Trans Raekore (Route 3)	Asphalt flat road	31.7	106
Seba - Tardamu	Jl. Masjid An-Nur Seba (Route 2)	Asphalt flat road	2	8

*Average travel time of a cargo truck (non-container) with a maximum capacity of 12 tons.

Based on the data in Table 31 the time dt_p for a round-trip to the Port of Biu can be calculated when using the Trans Seba Bolou road section or route 1 (chosen because it is the fastest option), plus the rest time of the driver on the way and also the truck dwelling time at the disrupted port. Figure 41 shows the condition of the Trans Seba Bolou or Route 1 road in 2021 (Ministry of Public Works and Housing, 2022). After calculating and consulting with experts, we estimated dt_p value for the Port of Biu at 2.6 hours and for Tardamu port at 0.26

hours. After obtaining the dt_p value for each alternative port (or airport) p, we can determine the $N_p(t)$ value for each p at the normal time t. Table 32 shows the results of the $N_p(t)$ calculation.

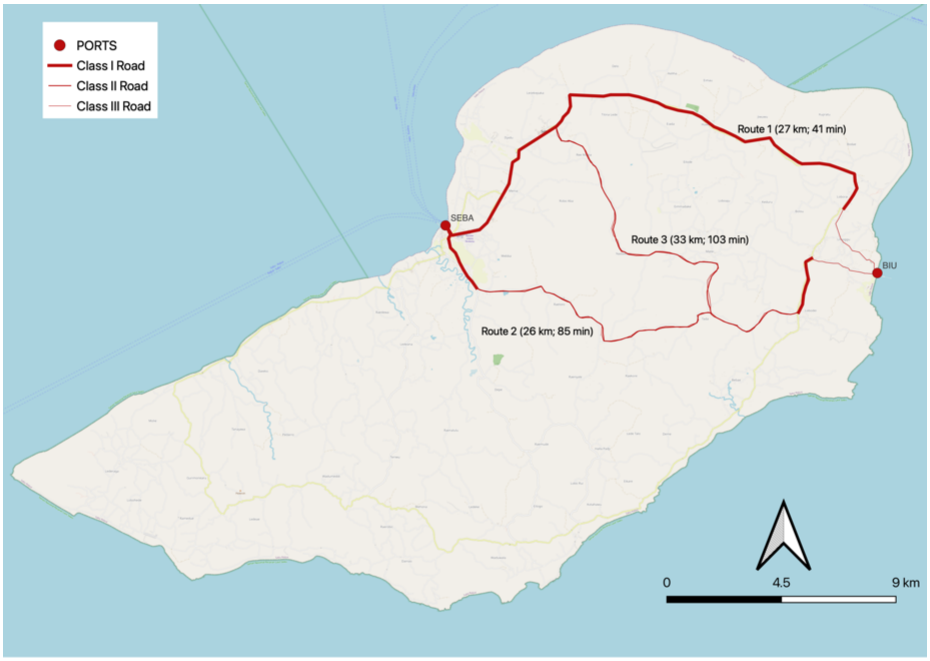


Figure 40. Spatial distribution of port hinterland network in Sabu Island

Figure 41. Trans Seba Bolou Road/Route 1 (asphalt flat road) in 2021 (Courtesy Ministry of Public Works and Housing, 2022)

Table 32. Number of trucks needed to capture the port spare capacity per day

Port/airport	Daily available spare capacity (DWT) (SC_p)	Average round trip travel time in hours (dt_p)	Minimum number of trucks* needed to capture the port spare capacity per day $N_p(t)$
Biu	535	2.6	5
Tardamu (airport)	200	0.26	1
		Total	6

*) Cargo truck (non-container) with a maximum load capacity of 12 tons

Based on the results of the empirical observations shown in Table 32, Sabu Island requires a minimum resource of six trucks per day to mobilize cargo transshipped at alternative ports to be sent to the Port of Seba for distribution to the hinterland. The relatively small size of Sabu Island has an advantage that the resources needed to mobilize cargo are not too extensive because the distance between ports and airports is small. However, the number of trucks required may change if a disaster affects the availability of roads connecting the ports on Sabu Island.

To summarize the empirical findings of the port-interland network on Sabu Island, we found some important things to highlight as follows. First, suppose the Port of Seba, a main port on Sabu Island, is disrupted and cannot run its operations. In that case, the spare capacity available at alternative ports is only around 50%. Secondly, to utilize the 50% spare capacity, Sabu Island must have at least six trucks with a capacity of 12 tons, connecting the Port of Seba as a disrupted port with other alternative ports on Sabu Island. Third, if the disaster is multi-impact, i.e., it affects the operations of more than one port simultaneously as well as ports-hinterland connectivity, the available spare capacity will be smaller than the initially calculated spare capacity (50%), and the resources needed to mobilize cargo will be more extensive.

5.1.3 Analysis of Sabu Island's Shipping Network Connectivity

In this section, we analyze Sabu Island's connectivity level as measured by cargo ship traffic visiting and leaving the island. This analysis aims to understand the spatial context of maritime connectivity connected to Sabu Island and how the Port of Seba is positioned and contributes to cargo flows on Sabu Island relative to other ports. The maritime connectivity level of Sabu Island is obtained from the calculation of the connectivity value of each cargo port i on Sabu Island. The connectivity value of each port in this case study is based on multiplying the maximum theoretical cargo ship capacity (in DWT) visiting the port i by the frequency of ship visits in a given period. Using Equation 2, the connectivity level of Sabu Island is the sum of the total connectivity of all individual ports i that can handle cargo on the island. In this case study, we consider all cargo vessels (including cargo-only vessels and mixed passenger-cargo vessels, such as Ro-Ro) because the ports on Sabu Island are designed to accommodate multiple vessel types.

AIS data cannot be used to calculate port connectivity on Sabu Island because AIS data does not cover traffic in small ports such as those on Sabu Island. In addition, INAPORTNET data is unavailable because these ports still need to install adequate information systems. To overcome this, we used two sources of data. These data were taken over six months, from October 2020 to April 2021. The first data is internal port call record data owned by the port authority in Sabu Island. This internal data records ships' entry and exit at the port, independent whether they are government-subsidized (Public Service Obligation) or commercial ships serving Sabu Island. The subsidized vessels analyzed in this study include pioneer ships and sea tolls vessels. The Pioneer Ship is a government program to improve connectivity and mobilize people and goods on the outer islands. The sea tolls is a program launched by the President of the Republic of Indonesia to reduce the price disparity of main commodity goods between the western and eastern parts of Indonesia. In principle, the sea highway implements fixed and regular sea transportation for cargo that connects regional collecting ports with small ports located in remote areas using large ships.

The second data type we use to analyze each port's connectivity level is publicly available data from the Maritime Transport Traffic Management Information System (SIMLALA). The data can be retrieved from the Ministry of Transport of the Republic of Indonesia website. The SIMLALA header data analyzed in this case study is shown in Table 33. SIMLALA data contains the approval permission for the assignment of Indonesian-flagged vessels where the ship was serving fixed and regular routes (liners) to support the sea transportation operations and connectivity in Indonesia. In the SIMLALA data, all Indonesian-flagged vessels are registered, and the routes served by these vessels are available to be analyzed. We use this SIMLALA data to ensure that the vessel records in the port call records provided by the port authority are complete. If a vessel is registered in SIMLALA but not in the internal port call records, we confirm with stakeholders whether or not the vessel visited the port. Cross-checking with data from SIMLALA improves data completeness and accuracy.

Table 33. Illustration of the dataset header from SIMLALA

Vessel Name	Route	Ship Cargo
ANDREW [TPK : 2010 Pst No. 6443/L] [IMO : 8805767] [CS : PNPS]	Atapupu - Anggrek - Badas Sumbawa - Balikpapan - Banjarmasin - Biringkassi - Bima - Benete - Batulicin - Bontang - Bungku - Bitung - Celukan Bawang - Gunung Batu Besar - Gresik - Gorontalo - Kotabaru - Tarjun - Kolaka - Kendari/Bungkutoko - Kalabahi - Makassar - Mamuju - Morowali - Masohi/Tersus Pt. Pertamina - Maumere - Ndao Baa - Nunukan - Samarinda - Sape - Seba - Pulang Pisau - Pantoloan/Donggala - Tanjung Perak - Toli-Toli - Leok - Labuhan Uki - Waikelo - Waingapu - Wini	Charcoal, Construction Tools, Clean Water, Asbestos, Asphalt, Fuel Oil, Building Materials, Construction Materials, Steel, Holder Stone, Grocery, Boldas Stone, Limestone, barite, Split Stone, Bauxite, Rice, Habiem Iron, Construction Iron, Plate Iron, Concrete, Palm Kernels, Shells, Cloves, Chocolate, FLy Ash, Dumb Truck, Cars, Jumbo Bag Cement, Cement, Cattle, Fertilizer, UREA, Copra, Coconut, Salt, Corn, Palm Kernel, Wheat Flour/Tapioca, Sago Flour, Oxygen Tube, LPG Tube, Pile, Electric Pole, Plywood, Bark, Sawn Wood, Plywood, Sawn Timber, Pulp, Sugar Sand, Quartz Sand, Building Sand, Rubber, Livestock Food
EVER TOP [TPK : 2002 Ka No. 3042/L] [IMO : 8627153] [CS : -]	Tanjung Perak - Gresik - Tuban - Probolinggo/Tanjung Tembaga - Semarang/Tanjung Emas - Pontianak - Kumai - Samarinda - Kendawangan - Pulang Pisau - Sampit - Banjarmasin - Tarjun - Bontang - Tarakan - Makassar - Biringkassi - Toli-Toli - Lola - Labuhan Uki - Tilamuta - Morowali - Sanana - Badas Sumbawa - Lembar - Bima - Kempo - Calabay - P. Ende - Waiwole - Marapokot - Leok - Atapupu - Labuan Bajo - Maumere - Waingapu - Waikelo - Seba - Raijua	Rice, Sugar, Salt, Wheat Flour/Tapioca, Corn, Staples, Palm Oil, Heavy Equipment, Construction Equipment, Iron, Cement, Animal Food, Plywood, Fertilizer
ARTHUR [TPK : 2012 HHa No. 2961/L] [IMO :] [CS : POTI]	Atapupu - Anggrek - Badas Sumbawa - Banjarmasin - Batulicin - Bima - Bontang - Biringkassi - Benete - Celukan Bawang - Pemenang - Bungku - Gresik - Gunung Batu Besar - Gorontalo - Kendari/Bungkutoko - Kotabaru - Kalabahi - Kolaka - Kwandang - Lembar - Labuhan Uki - Mamuju - Makassar - Morowali - Namlea - Ndao Batutua - Pantoloan/Donggala - Palopo - Tenau/Kupang - Tarjun - Tilamuta - Sape - Seba - Samarinda - Sorong - Tanjung Perak - Waikelo - Waingapu - Wini	Clean Water, Construction Tools, Asbestos, Asphalt, Fuel Oil, Building Materials, Construction Materials, Steel, Project Materials, barite, Grocery, Boldas Stone, Granite Stone, Holder Stone, Limestone, Bauxite, Rice, Habiem Iron, Split Stone, Construction Iron, Plate Iron, Screw Iron, Concrete, Palm Kernels, Shells, Cloves, Corn, Crew, Jumbo Bag Cement, Cement, Fertilizer, UREA, RBD Olein, Nickel, Wheat Flour/Tapioca, Sago Flour, Rubber, Copra, Coconut, Oxygen Tube, LPG Tube, Bark, Sawn Wood, Plywood, Rattan, Sawn Timber, Cattle, Vehicle, Dumb Truck, Car, Pile, Electric Pole, Animal Food, Wheat, Sand Sugar, Quartz Sand, Building Sand, Salt, Pipe, Pulp, Manganese Ore, Chemical, Chocolate, Paper

Based on the empirical data of ship voyage plans we retrieved from SIMLALA, we then analyzed Sabu Island's connectivity by calculating all ship visits to the ports on Sabu Island (i.e., the Ports of Seba and Biu). We used equation 1 to calculate the individual connectivity per port, and then we summed up the connectivity value per port into an overall connectivity value for Sabu Island. Our dataset spans from October 6, 2020, to April 4, 2021. We assumed that the connectivity of Sabu Island was normal during this period, as no events disrupted port operations and shipping services on Sabu Island.

Table 34. Cargo shipping connectivity in Sabu Island from October 2020 - April 2021

Rank	Port	Port connectivity (in DWT), C_{ij}	Average connectivity per day (in DWT / Day)
1	Seba	260,640	1,448
2	Biu	91,260	507
Sabu Island's connectivity		**351,900**	**1,955**

The calculation results of cargo shipping connectivity in the October 2020 - April 2021 period at each port on Sabu Island are shown in Table 34. In the table, the calculation results are sorted from the port with the highest to the one with the lowest connectivity. Based on the calculation results, Sabu Island has connectivity with a cargo ship capacity of 351,900 DWT or an average of 1,955 DWT per day under normal conditions.

The Port of Seba has the highest shipping connectivity, followed by the Port of Biu. It was found that the Port of Seba is the most critical in supporting the connectivity of Sabu Island, with almost three times the connectivity compared to the Port of Biu. The Port of Seba handles 75% of the total flow of goods on Sabu Island, while the Port of Biu handles the remaining 25%. Suppose the Port of Seba experiences a total operational disruption and cannot work. In that case, there is the potential that Sabu Island will lose 75% of its capacity to send or receive goods. Figure 42 shows the spatial distribution of the ports in Sabu Island and the centrality level based on DWT connectivity in each port. The red dots indicate the ports on Sabu Island, and the larger red circle indicates a higher centrality level on Sabu Island.

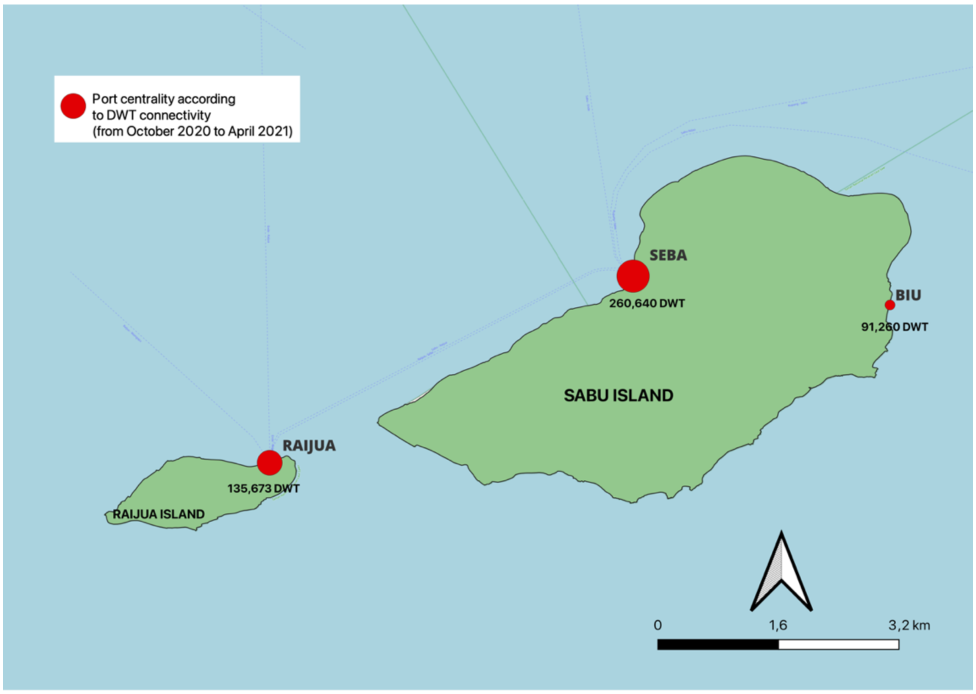


Figure 42. Spatial distribution and centrality of ports for Sabu Island (Adapted from Open Street Map)

After analyzing the connectivity level at Sabu Island, we continued by analyzing the shipping services directly connected to the Port of Seba. We analyzed this to map the ports connected to the Port of Seba under normal circumstances. This mapping will be useful as a benchmark to determine whether there is a significant change in the connectivity of the Port of Seba when affected by a disaster. Our analysis included inbound and outbound analysis at the Port of Seba, along with the total capacity of cargo vessels serving the route in DWT. To analyze shipping services directly connected to the Port of Seba, we used internal data provided by the Port Authority of the Port of Seba, which was cross-checked with data from SIMLALA. Table 35 shows the origins and destinations of shipping services directly connected to the Port of Seba between October 6, 2020, and April 4, 2021.

Table 35. List of cargo shipping services that connected to the Port of Seba in 2020 and 2021 (6 months period before the disaster)

Inbound Edge	**Cargo shipping capacity (DWT)**	**Outbound Edge**	**Cargo shipping capacity (DWT)**
Raijua - Seba	115,940	Seba – Raijua	99,386
Tenau/Kupang - Seba	55,940	Seba – Ndao Ndao	57,199
Ndao Baa - Seba	45,605	Seba – Ndao Baa	44,326
Ndao Ndao - Seba	43,155	Seba – Bitung	18,483
		Seba – Ambon	18,032
		Seba – P. Ende	14,626
		Seba - Waingapu	8,587
Total	260,640		260,640

Figure 43 shows the spatial distribution of shipping services directed towards the Port of Seba or inbound edges. In the figure, the size of the vertices shows the total connectivity of the ports relative to other ports in the region. Four ports serve shipping services to the Port of Seba, including Tenau/Kupang, Ndao Baa, Ndao Ndao, and Raijua Ports. In general, inbound traffic services to the Port of Seba have *short hop routes*, so there are no direct point-to-point ship services from distant ports. The thickness of the edges represents the capacity of the shipping services for each pair of ports. Shipments from Tenau/Kupang to the port of Seba have the highest capacity. This is because the port of Tenau/Kupang is a hub or transshipment port for large ocean-going tonnage vessels, specifically carrying goods from Java or the western part of Indonesia. From Tenau/Kupang Port, the cargo is sent to the Port of Seba and other regional collector ports.

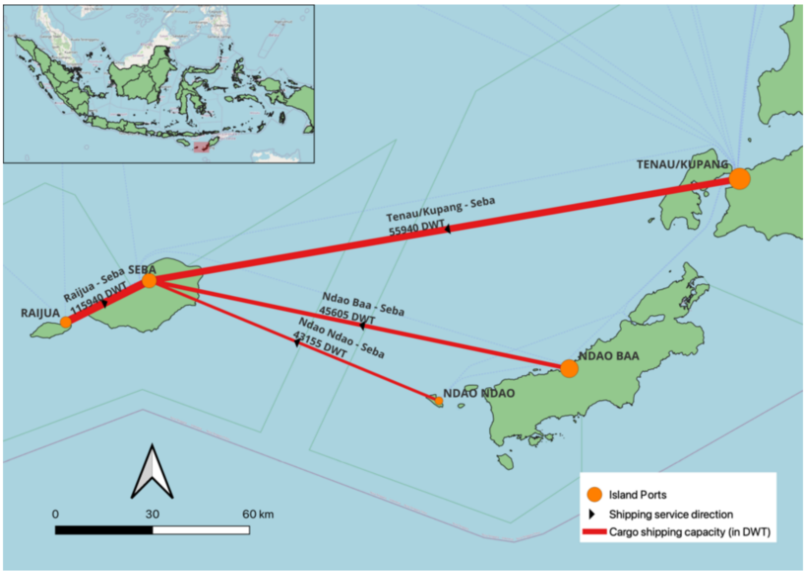


Figure 43. Inbound edges of cargo ships connected to the Port of Seba in 2020-2021

A visualization of the spatial distribution of shipping services from the Port of Seba is shown in Figure 44. There are a total of seven ports that are the main destinations for shipping goods originating from Seba Port. The ports of Ndao Baa, Ndao Ndao, Raijua, Ende Island, and Waingapu are the ports closest to Seba Port and are the destinations of the short hop routes. The proportion of the shipping service capacity of these short hop routes is around 85%. The remaining 15% is long-distance direct connectivity from the Port of Seba to the Port of Bitung and the Port of Ambon. These long-haul services generally form circular shipping routes of large vessels, where the Port of Seba is the final destination.

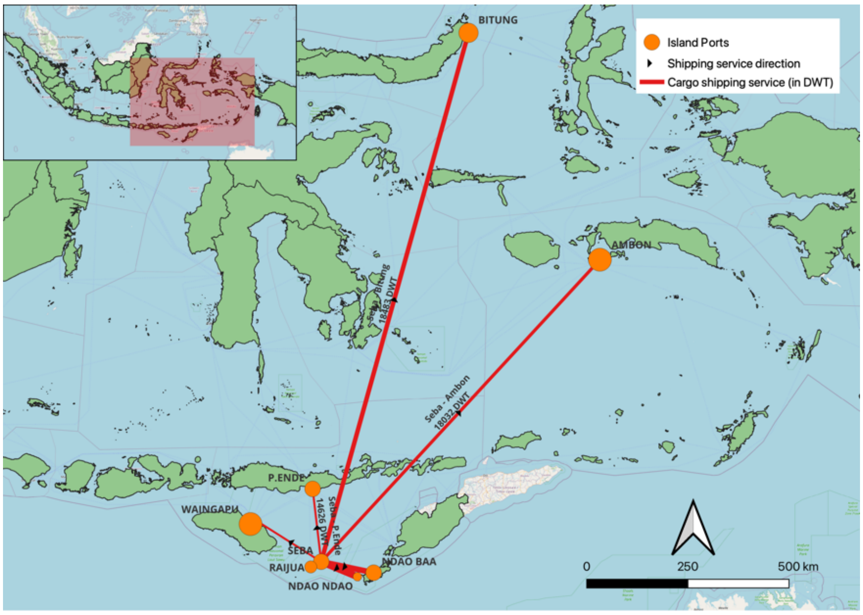


Figure 44. Outbound edges of cargo ships connected to the Port of Seba in 2020 – 2021

5.2 Phase 2: Resilience Curve Analysis

This section describes the implementation of phase 2 in the empirical evaluation method proposed in this study, the resilience curve analysis. This section will describe how Tropical Cyclone Seroja affected port operations at the Port of Seba over time using the resilience curve method we conceptualized in Chapter 2. As a first step, we need to select the primary indicators to measure changes in the performance of the Port of Seba before and after being affected by the disaster. In this case study, the selected performance indicator is related to the Port's ability to serve the needs of the Sabu Island community to load and unload goods or cargo.

The main metric used to measure this is Cargo Vessel Capacity (CVC_{Cargo}). CVC_{Cargo} is an indicator that measures the port's ability to serve public needs by calculating the theoretical maximum capacity of cargo ships served by the Port of Seba within a certain period. This CVC_{Cargo} indicator is measured using Deadweight Tons (DWT). The formula used to calculate CVC_{Cargo} adds up the maximum theoretical capacity of each ship that visits the Port of Seba at a certain time. An example of CVC_{Cargo} calculation is as follows. Suppose the Port of Seba serves two vessels in two days, which have a theoretical maximum capacity of 300 and 400 DWT; then CVC_{Cargo} at the Port of Seba is 700 DWT in that period. This 700 DWT is analogous to the ability of the Port of Seba to serve the public in facilitating the transportation of goods on Sabu Island. Experts have validated the use of CVC_{Cargo} as the main indicator, and they agreed that CVC_{Cargo} is the most important indicator of service performance used by non-commercial public ports in Indonesia.

Internal port call document data owned by the Seba port authority and data from SIMLALA were used to develop a resilience curve in this case study. The port call documents were studied for one year, from January 2021 to January 2022. These internal port call records record incoming and outgoing cargo vessels at the Port of Seba. Data from SIMLALA was used to cross-check whether the vessels recorded in the Vessel Operation Plan (RPK) match the data recorded in the Port of Seba internal port call documents. If there were discrepancies, the actual findings were checked by stakeholders at the Port of Seba. The results confirmed by the stakeholders will become the basis for developing the empirical resilience curve for the Port of Seba. The resilience curve is shown in Figure 45.

Based on the empirical resilience curve in Figure 45, we identified six changepoints in the graph that show significant changes in behavior over time. Each changepoint indicates an event significantly changing the port's performance behavior. These changepoints will be useful in determining the phases in the resilience cycle, such as the preparation, response, recovery, and adaptation phases. A detailed description of the six change points is shown in Table 36.

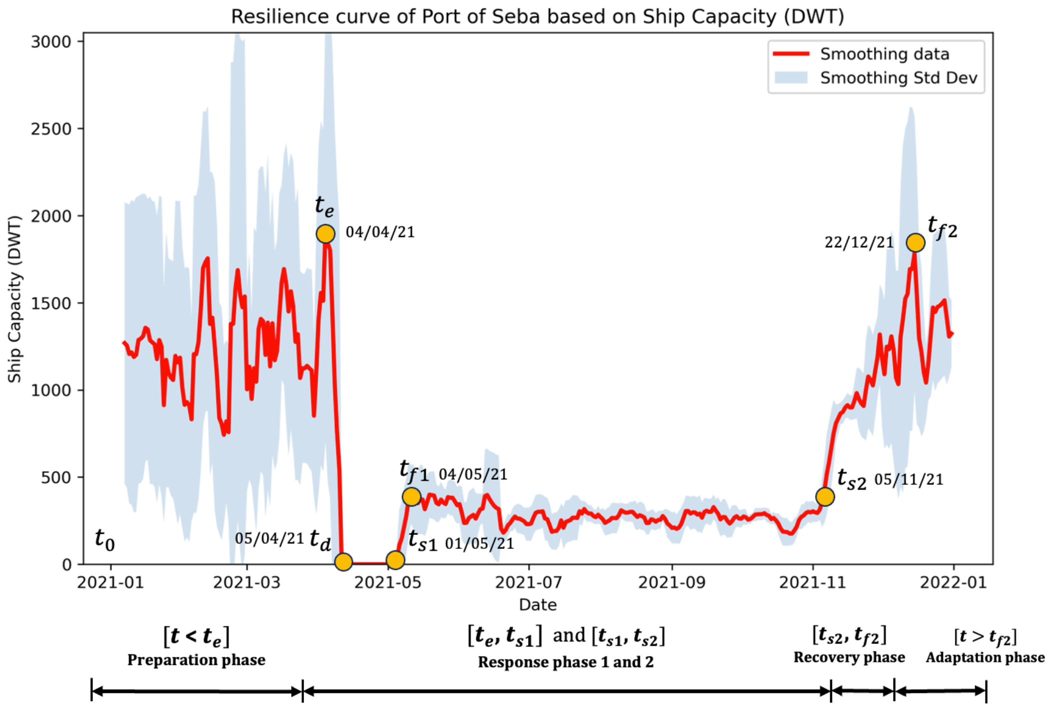


Figure 45. The empirical resilience curve of Port of Seba presented as a 3-day moving average

Table 36. Key changepoints detailed in the empirical resilience curve of the Port of Seba

Point symbol	Date point	Events
t_e	April 4, 2021	A tropical cyclone (Tropical Cyclone Seroja) with maximum sustained winds of 102 km/h struck the Port of Seba on Sabu Island, East Nusa Tenggara Province.
t_d	April 5, 2021	UPP Class III Seba announced a temporary port closure due to the stranding of MV Cantika Lestari 10C and the ongoing tropical cyclone Seroja.
t_{s1}	May 1, 2021	UPP Class III Seba announced that due to the Cantika Lestari 10C still being stranded at the main berth, the Port of Seba can only accept the loading and unloading goods with rede transport by using a part of the berth that was not affected.
t_{f1}	May 4, 2021	The Port of Seba has experienced increased ship visits for loading and unloading goods. However, capacity remains limited due to the need to evacuate the stranded MV Cantika Lestari 10C.
t_{s2}	November 23, 2021	MV Cantika Lestari 10C was finally successfully lifted and evacuated after being stranded for seven months at the main berth of the Port of Seba.
t_{f2}	December 22, 2021	The performance of the port of Seba has reached a point similar to the one before the tropical cyclone Seroja. This indicates that the cargo ship traffic for the loading and unloading goods in the port of Seba has returned to what it was before the disaster.

Based on the constructed empirical resilience curve, we calculated the resilience attributes of the Port of Seba for tropical cyclone Seroja. The theoretical formula we used in the calculation can be seen in Chapter 2, which discusses the theoretical foundation of this research.

The calculation results of each resilience attribute, along with the theoretical formula and justification, are shown in Table 37.

Table 37. The empirical resilience attributes of the Port of Seba, along with its reasoning based on the empirical resilience curve

Resilience attributes	Theoretical formula	Empirical value	Reasoning
Robustness	Residual performance, $f(t_d)$	0 DWT / day	$f(t_d)$ shows the residual performance of the port when it was under the worst impact due to tropical cyclone Seroja (t_d). One day after the disaster (April 5, 2021), the Port of Seba was completely closed due to the stranded MV Cantika Lestari 10C, causing the loading and unloading of cargo at the main berth to be unavailable.
Vulnerability	Depth of performance decline, $f(t_0) - f(t_d)$	1,448 DWT / day	Based on the results of empirical analysis, the average cargo vessel capacity visiting and leaving Seba Port is 1,448 DWT / day, and when affected by Tropical Cyclone Seroja, it became 0 DWT. This indicates that the level of vulnerability (performance loss) of the Port of Seba to tropical cyclone disasters was equivalent to 1,448 DWT.
Responsiveness (Phase 1)	Duration of time spent at response phase 1 $(t_{s1} - t_e)$	26 Days	The first responsiveness phase from Tropical Cyclone Seroja (April 4, 2021) lasts until the port resumes limited operations (due to the stranding of MV Cantika Lestari 10C) on May 1, 2021.
Responsiveness (Phase 2)	Duration of time spent at response phase 2 $(t_{s2} - t_{s1})$	206 Days	The second responsiveness began with the port resuming limited operations (May 1, 2021) until the evacuation of the MV Cantika Lestari 10C (November 23, 2021) to successfully restore the capacity of the Port of Seba.
Rapidity	Duration of time spent in the recovery process $(t_{f2} - t_{s2})$	29 Days	The rapidity of the Port of Seba started with the successful evacuation of MV Cantika Lestari 10C (November 23, 2021) until the port traffic performance returned to normal (December 22, 2021).
Recoverability	Speed of recovery, $\frac{df(t_{s2})}{dt}$	33 DWT / Day	The value for recoverability is determined from the difference between the average residual performance from $[t_{f1}, t_{s2}]$ and the performance point at which it is declared to have returned to the original traffic performance t_{f2}, and then divided by the total duration spent from $[t_{s2}, t_{f2}]$. Thus, the value can be determined using (1934 - 365) DWT / 47 Days = 33 DWT / Day.

The main indicator to create the resilience curve is the port's ability to serve cargo shipping, as measured by the Cargo Vessel Capacity (CVC_{Cargo}) metric. The results of this analysis can be used as a reference to illustrate how the Port of Seba or a similar port will perform when affected by a Tropical Cyclone natural disaster. The resilience curve analysis identifies critical points in the form of changepoints that can be used to determine the phases of the resilience cycle, such as the preparation, response, recovery, and adaptation phases, which can in turn be used to conduct a more in-depth analysis of what happened in each phase.

The resilience curve can also be used to calculate resilience attributes. These resilience attributes are the components that define the overall resilience of the Port of Seba. Resilience attributes of *robustness* or *vulnerability* can determine the ability of the Port of Seba to withstand damage from tropical cyclones. We found that the robustness value of Seba Port is 0 DWT/day, and the vulnerability is 1,448 DWT/day. UPP Class III Seba announced that the port was temporarily closed after the disaster. This policy prevented ships from entering and exiting the port, resulting in a residual performance of 0 DWT. Meanwhile, the *vulnerability* value was obtained from the decrease in the average value of CVC_{Cargo} , compared to the situation before the disaster.

The *responsiveness* attribute can determine how agile the Port of Seba is in preparing resources and restoring operational capacity. Based on empirical data, we found that the total *responsiveness* time needed to restore full operational capacity for the Port of Seba was 235 days. The efforts to restore port operational capacity include initiating cooperation, obtaining the resources needed, and determining effective strategies.

When the port capacity has returned to its original state, the resilience attributes *rapidity* or *recoverability* can be used to measure how quickly the Port's performance was able to return to a pre-disaster state. The value of the Port's *rapidity* for the Port of Seba was 29 days, and the recoverability was 33 DWT per day, starting from the time the operational capacity of the port fully recovered until the performance (measured by CVC_{Cargo}) reached a value comparable to the pre-disaster period. The development of this resilience curve analysis can later be used to analyze the resilience of Seba port more deeply, such as knowing the cause of the port *robustness* to become 0 DWT, and which interventions were made by stakeholders that resulted in these port *responsiveness*, *rapidity*, and *recoverability* values. Further analysis is carried out in the next phase below.

5.3 Phase 3: Disaster Impact Analysis

This section describes the third phase of the empirical analysis of port resilience: Disaster Impact Analysis. This phase explores the impact of the tropical cyclone at the level of the Port of Seba and the spatial network of Sabu Island, including the port-hinterland network and the shipping connectivity of Sabu Island. The analysis in this phase is divided into three subsections. Subsection 5.3.1 analyzes the impact of tropical cyclone Seroja on the socio-technical components of the Port of Seba. This section is important to understand what happened at point t_d of the resilience curve and to answer why the port's port resilience is 0 DWT. Section 5.3.2 discusses how tropical cyclone Seroja impacted the ports-hinterland network on Sabu Island at point t_d in the resilience curve and whether the impact contributed to the resilience of the Port of Seba. Finally, subsection 5.3.3 discusses the impact of Tropical Cyclone Seroja on the shipping connectivity of Sabu Island and the vessel connections to the Port of Seba.

5.3.1 Disaster Impact Analysis on the Port of Seba's Socio-Technical Components

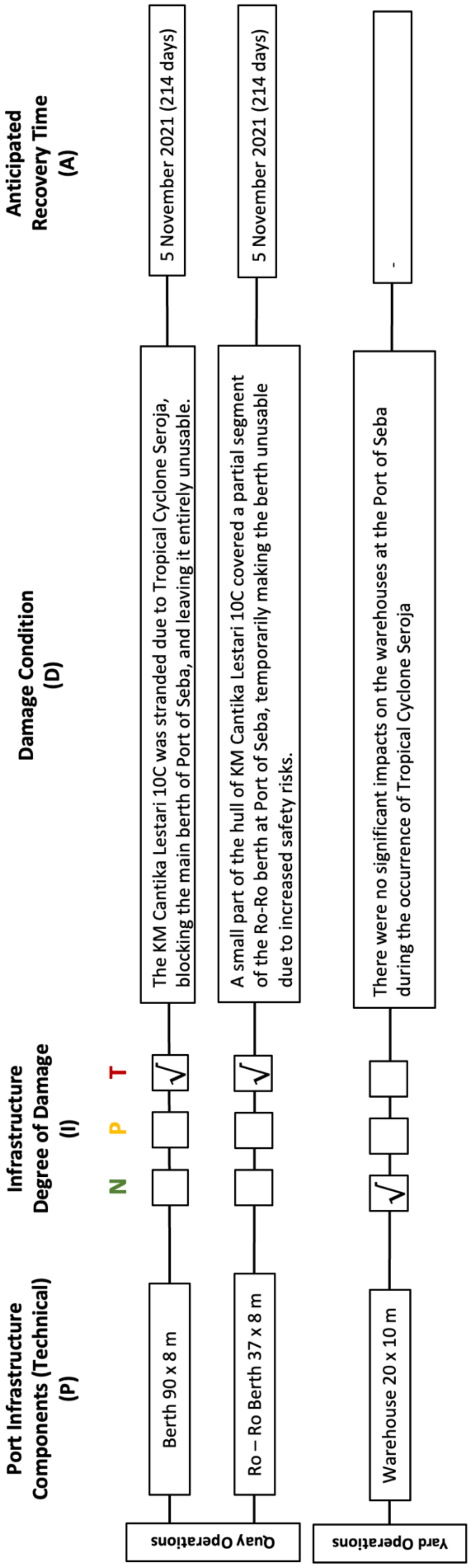
This subsection presents the analysis results regarding how Tropical Cyclone Seroja's April 4, 2021 impact affected the socio-technical components at the Port of Seba. Specifically, this section describes what happened to the components at the Port of Seba at the t_d point in the resilience curve shown in Figure 45. To analyze the impact of the tropical cyclone on socio-technical components at the Port of Seba, we processed data from the Focus Group Discussion (FGD) with the Research and Development Agency for Sea Transportation (BALITBANGHUB) of the Ministry of Transportation of the Republic of Indonesia. We conducted the focus group discussion online due to the social movement restriction measures because of the COVID-19 pandemic. In addition, we used this FGD technique because there were no publicly released field survey reports related to the Seroja tropical cyclone disaster. In addition to using data from the Focus Group Discussion, data derived from 13 articles in the mass media were also used (list of documents [5-1] to [5-13] at the end of this chapter). The mass media findings were validated through focus group discussions with stakeholders at the Ministry of Transportation, Republic of Indonesia.

The PIDA sheet was used in this phase to determine the extent of the impact of Tropical Cyclone Seroja on the socio-technical components at the Port of Seba. Figure 38 is used as a reference to check the impact of the disaster on each socio-technical component at the Port of Seba. Technical components located in the Port of Seba are limited due to the relatively small size of the port. The analysis of technical components carried out includes the main berth with a size of 90 x 8 meters, the Ro-Ro ship berth with a size of 37 x 8 m, and the warehouse for storing cargo with a size of 20 x 10 m.

Figure 46 shows the examination results using the PIDA sheet on the technical components of the Port of Seba. The analysis shows that the technical component most affected by tropical cyclone Seroja is the berth, both the berth for general cargo and the berth for Ro-Ro vessels. The main cause was the MV Cantika Lestari 10C stranding, sailing near the Port of Seba during the cyclone, as shown in Figure 47. The MV Cantika Lestari 10C is a 1310 GT or 598 DWT Ro-Ro vessel. Tropical Cyclone Seroja dragged MV Cantika Lestari 10C to the berth, breaking some segments of the berth, which resulted in the ship getting stuck. Meanwhile, the warehouse used for storage was not damaged, and there was no significant effect of tropical Cyclone Seroja on the physical condition of the warehouse.

The results of the analysis of the social components of the Port of Seba are shown in Figure 48. There were no casualties from this incident. The data processing results show that the officers at UPP Class III Seba were partially affected, especially those who live in the trajectory of tropical cyclone Seroja. Meanwhile, officers who live in official houses were unaffected because the house's location was not impacted by the tropical cyclone trajectory. Figure 49 shows the condition of the official residence after the tropical cyclone Seroja incident.

The social component that was severely affected was the port operational workforce. Most of these personnel reside in areas that were affected by the tropical cyclone trajectory. Some examples of houses affected by tropical cyclone Seroja are shown in Figure 50. The severe damage to these houses eventually led to the operational workforce being temporarily unavailable due to having to evacuate to other places or volunteering to help families and communities more severely affected by tropical cyclone Seroja on Sabu Island. As such, the Port of Seba did not have an operational workforce to run port operations following tropical cyclone Seroja. The return of the social component to actively support the Port of Seba operations varied, ranging from 8-27 days.



	Port Infrastructure Components (Technical) (P)	Infrastructure Degree of Damage (I) N	P	T	Damage Condition (D)	Anticipated Recovery Time (A)
Quay Operations	Berth 90 x 8 m	☐	☐	✓	The KM Cantika Lestari 10C was stranded due to Tropical Cyclone Seroja, blocking the main berth of Port of Seba, and leaving it entirely unusable.	5 November 2021 (214 days)
	Ro – Ro Berth 37 x 8 m	☐	☐	✓	A small part of the hull of KM Cantika Lestari 10C covered a partial segment of the Ro-Ro berth at Port of Seba, temporarily making the berth unusable due to increased safety risks.	5 November 2021 (214 days)
Yard Operations	Warehouse 20 x 10 m	✓	☐	☐	There were no significant impacts on the warehouses at the Port of Seba during the occurrence of Tropical Cyclone Seroja	-

Figure 46. PIDA results for Technical Components of the Port of Seba. For Infrastructure Degree of Damage, N = Not affected, P = Partially affected, T = Totally unusable

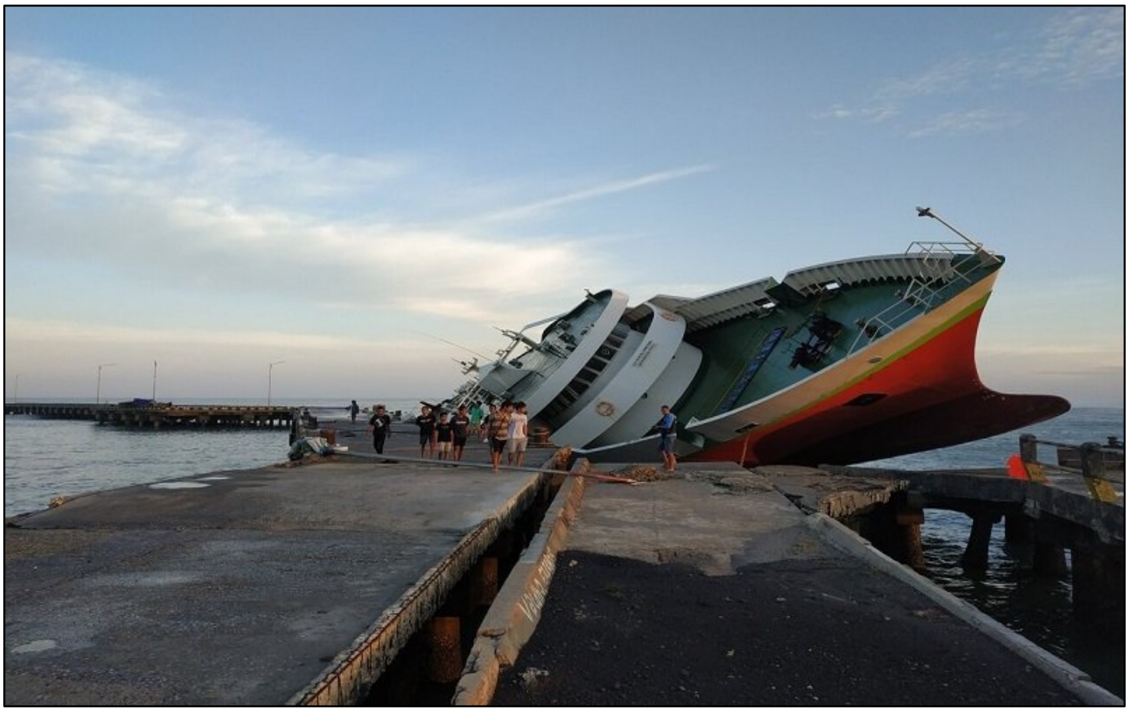


Figure 47. MV Cantika Lestari 10C stranded at the main berth, partially blocking the ro-ro berth at the Port of Seba (Courtesy of UPP Class III Seba)

After analyzing the impact of the disaster using PIDA, the analysis results were visualized again using a block diagram. Figure 51 shows a block diagram of operations at the Port of Seba at point t_d with color codes from the analysis results of PIDA. The figure has four colors: red, yellow, green, and gray. The red color indicates that the component is completely dysfunctional. Yellow indicates that the disaster affected the component, but it can still function, even only partially. Green indicates that the component is not affected and can function normally. The gray color indicates a component that is beyond the responsibility of the first-tier actors of Seba Port.

Figure 51 can be interpreted as follows. At point t_d, none of the operations at the Port of Seba could be carried out, including the operations on ships, quays, or storage yards. In ship operations, the loading and unloading of cargo could not be carried out because the stevedoring labor could not work due to the impact of tropical cyclone Seroja. This stevedoring workforce is important because loading and unloading goods, either from the quay to the ship or from the rede ship to the large ship, relies on human labor.

Quay operations could not function because the technical and social components were affected. Ships could not dock at the Port of Seba due to berth damage and the stranding of the MV Cantika Lestari 10C ship. As for the social component aspect, loading and unloading labor at the Port of Seba was not available because the workforce was affected by the disaster. Finally, the storage yard operations were also unable to function due to the unavailability of labor due to the disaster. Although the technical components of the storage yard were not significantly affected, the absence of port operational labor made operations in this storage yard unable to function.

The main benefit of the analysis results shown in Figure 51 is that it makes it easier for stakeholders to determine the main causes of the disrupted port operations. For example, in the port of Seba, UPP Class III Seba could not carry out quay operations because of the stranded ship that was stuck at the berth, and the port had to be closed. Meanwhile, storage yard operations were also unable to serve due to the lack of port operational workforce, all of whom were direct and indirect victims of tropical cyclone Seroja. Using block diagrams combined with the assessment results from PIDA, as shown in Figure 51, can be a very useful instrument for stakeholders to prioritize the protection of certain components that are proven to be the root cause during port performance disruptions.

	Port Infrastructure Components (Technical) (P)	Infrastructure Degree of Damage (I) N	P	T	Damage Condition (D)	Anticipated Recovery Time (A)
Ship operations	4 Harbor master	☐	√	☐	No casualties occurred. Following Tropical Cyclone Seroja, half of the UPP Class 3 Seba employees had their houses destroyed and requested temporary leave.	**N**: 13/04/21 (8 days)
	2 maritime traffic and transport services officer	☐	√	☐	No casualties occurred. Following Tropical Cyclone Seroja, half of the UPP Class 3 Seba employees had their houses destroyed and requested temporary leave.	**N**: 13/04/21 (8 days)
	5 – 10 Stevedoring labor	☐	☐	√	No casualties. All of stevedoring labors were unable to resume work immediately as they had to evacuate or volunteer to assist disaster victims whose homes were being destroyed.	**P**: 18/04/21 (13 days); **N:** 25/04/21 (20 days)
Quay operations	1 Port facility and compliance officer	√	☐	☐	No casualties. The officer was still assigned to monitor the port.	-
	2 maritime traffic and transport services officer	☐	√	☐	No casualties occurred. Following Tropical Cyclone Seroja, half of the UPP Class 3 Seba employees had their houses destroyed and requested temporary leave.	**N**: 13/04/21 (8 days)
	5 – 10 Stevedoring labors	☐	☐	√	No casualties. All of stevedoring labors were unable to resume work immediately as they had to evacuate or volunteer to assist disaster victims whose homes were being destroyed.	**P**: 18/04/21 (13 days); **N:** 01/05/21 (27 days)
Stacking yard operations	1 Port facility and compliance officer	√	☐	☐	No casualties. The officer was still assigned to monitor the port.	-
	2 Warehouse manager	☐	☐	√	No casualties. The operational labors could not resume work immediately as they had to evacuate or volunteer to assist disaster victims whose homes were being destroyed.	**N**: 18/04/21 (13 days)
	35 – 45 Stevedoring labors	☐	☐	√	No casualties. The operational labors could not resume work immediately as they had to evacuate or volunteer to assist disaster victims whose homes were being destroyed.	**P**: 18/04/21 (13 days); **N:** 25/04/21 (20 days)
	3 Counters	☐	☐	√	No casualties. The operational labors could not resume work immediately as they had to evacuate or volunteer to assist disaster victims whose homes were being destroyed.	**N**: 15/04/21 (10 days)
	3 Foremen	☐	☐	√	No casualties. The operational labors could not resume work immediately as they had to evacuate or volunteer to assist disaster victims whose homes were being destroyed.	**N**: 13/04/21 (8 days)

Figure 48. PIDA results for Social Components of the Port of Seba. For Infrastructure Degree of Damage, N = Not affected, P = Partially affected, T = Totally unusable

Figure 49. The condition of the Ministry of Transportation Official Residences near the Port of Seba after tropical cyclone Seroja (Courtesy of Ministry of Transportation)

Figure 50. One example of a house for an operational laborer affected by the tropical cyclone Seroja (courtesy of UPP Class III Port of Seba)

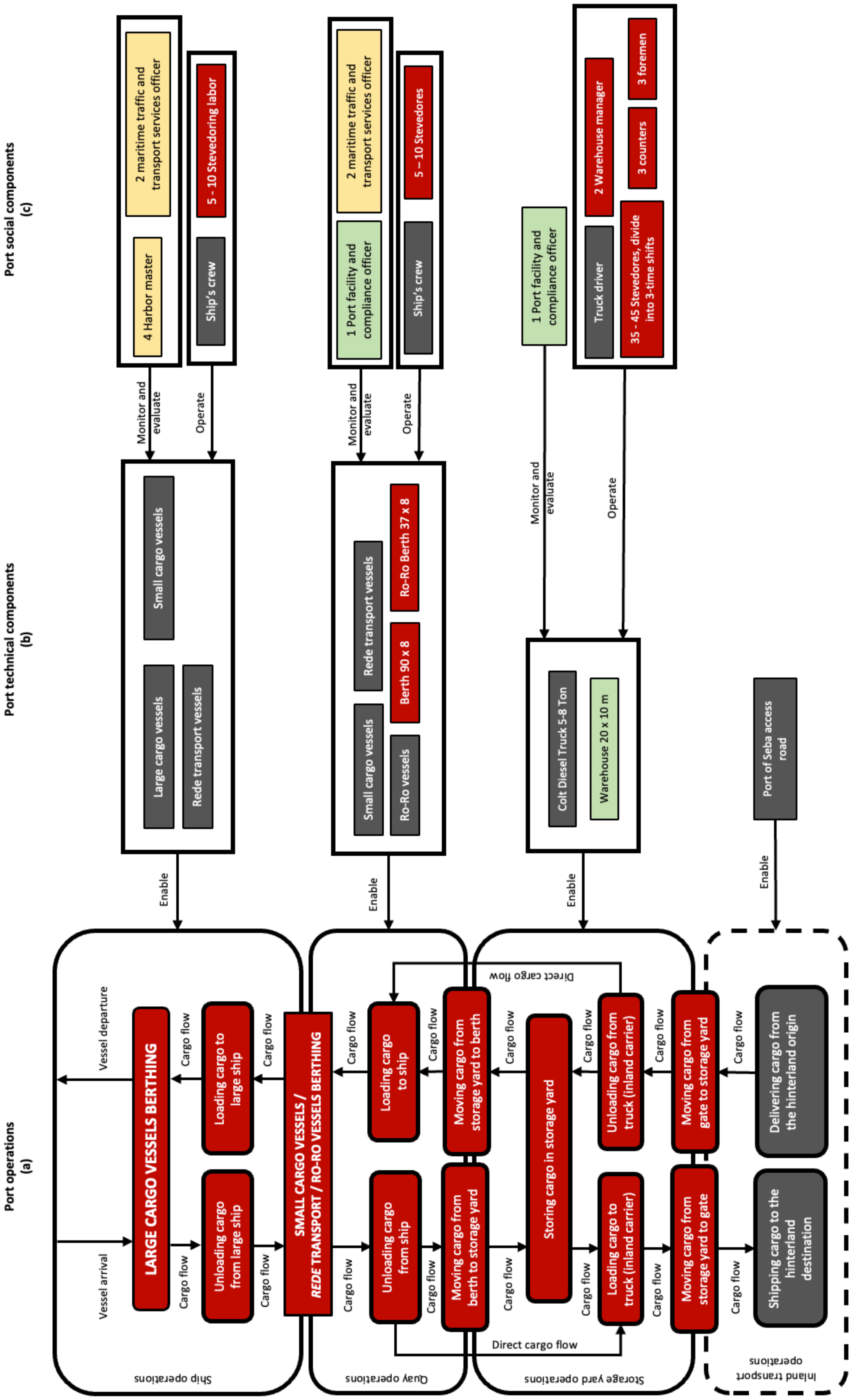


Figure 51. Block diagram derived from PIDA analysis result

5.3.2 Disaster Impact on the Sabu Island's Ports-Hinterland Network Connectivity

In this subsection, the analysis focuses on the impact of the disaster on the connectivity of the ports-hinterland network on Sabu Island. The analysis in this section has two stages. The first stage is a vertex-focused analysis of the ports-hinterland network, focusing on the impact of tropical cyclone Seroja on spare capacity at alternative ports on Sabu Island. The main metric used to measure the change was the Spare Capacity Replacement Index at the time t_d ($SCRI_p(t_d)$). The change in the $SCRI_p$ value indicates that the port affected by tropical cyclone Seroja is the Port of Seba and other ports on Sabu Island. This analysis used the internal disaster management document of the Sabu Raijua Regency Regional Disaster Management Agency (BPBD). Table 38 shows the results of the $SCRI_p$ changes.

Table 38. Changes in spare capacity at alternative ports in Sabu Island following the disaster

Alternative ports on Sabu Island	Daily Spare Capacity at the time t_d in DWT ($SC_p(t_d)$)	Spare Capacity Replacement Index per Port at time t_d ($SCRI_p(t_d)$)	% change
Biu	290	20%	-16%
Tardamu (Airport)	110*	7.5%*	-5.5%

* This figure applies when an emergency occurs where Tardamu Airport is only open to receive goods. During normal operations, Tardamu Airport only serves flight services for passengers.

Based on the results of the analysis shown in Table 38, it is found that tropical cyclone Seroja had a multi-vertex impact. This is known from the changes in the value of $SCRI_p$ at alternative ports and airports on Sabu Island. At the Port of Biu, there was a 16% reduction in spare capacity caused by the reduction in stevedoring and operational labor available at Biu Port. Several stevedoring workers at the Port of Biu come from the western part of Sabu Island, where their relatives were victims of the tropical cyclone Seroja disaster. However, the Port of Biu did not suffer from significant damage of the physical infrastructure or technical components. A similar impact also occurred at Tardamu Airport. The airport was not significantly affected in terms of physical infrastructure. Still, many airport workers and stevedores could not work because their homes or relatives were affected by tropical cyclone Seroja. This result shows that the reduced spare capacity at an alternative port or airport is not always due to damage to its technical components but also due to the absence of social components to provide operational services at the ports or airports.

The second analysis stage in this subsection focuses on the edges of the road network that connects the Port of Seba with other ports on Sabu Island. The main objective of this second stage analysis is to determine whether there was a change in the road network's capacity. The number of trucks (cargo trucks with a capacity of 12 tons) needed to capture the port spare capacity per day after the disaster ($N_p(t_d)$) is the main metric to measure the change in road capacity. To be able to calculate the value of ($N_p(t_d)$), the value of the average one-way travel time for each road section using trucks with a general cargo capacity of 12 tons at t_d, or $dt_p(t_d)$, is required. To calculate the value of $dt_p(t_d)$, data obtained from documents from the Ministry of Public Works and Housing (PUPR) on road damage that occurred at time point t_d was used, and interviews were conducted with several trucking businesses on Sabu Island to determine the travel time between ports under these conditions. Table 39 lists the road sections affected by tropical cyclone Seroja and how it affects the value of $dt_p(t_d)$.

Table 39. The impact of tropical cyclone Seroja on the road sections in Sabu Island following the tropical cyclone Seroja at point t_d

Origin - Destination	Road segment name	Terrain / Type	Distance (km)	Average one-way Travel Time at t_d (Min)	Condition
Seba - Biu	Jl. Trans Seba Bolou (Route 1)	Asphalt flat road	27.2	80	Normal
Seba - Biu	Jl. Masjid An-Nur Seba (Route 2)	Asphalt flat road	26	Not passable	Covered by debris and flooding
Seba - Biu	Jl. Trans Raekore (Route 3)	Asphalt flat road	31.7	106	Normal
Seba - Tardamu	Jl. Masjid An-Nur Seba (Route 2)	Asphalt flat road	2	Not passable	Covered by debris and flooding

From the analysis of the impact of the tropical cyclone on the road network, we found that the two roads affected were Route 2 (Masjid An-Nur Seba Road), which is an alternative route connecting the Port of Seba to the Port of Biu, but also the main route connecting the Port of Seba to Tardamu Airport. Some segments of this road were covered with debris and some were closed due to flooding. Figure 52 shows the Route 2 access road covered with debris and downed trees (Figure 52a) and sections of the road covered by floodwater (Figure 52b).

(a) **(b)**

Figure 52. Route 2 road section was covered with debris and fallen trees (a) and debris and floodwater (b) due to tropical cyclone Seroja (Courtesy of Ministry of Public Works and Housing, 2022)

After knowing how the direct impact of tropical cyclone Seroja on road sections on Sabu Island (which is indicated by a change in the value of $dt_p(t_d)$, the value of how many resource trucks can load general cargo with a capacity of 12 tons or $N_p(t_d)$ can be calculated. The value of $N_p(t_d)$ shows how the level of connectivity between alternative ports on Sabu Island and the Port of Seba through the hinterland. This connectivity considers the daily available spare capacity at each alternative port (SC_p) and the average round-trip travel time, which is the value of one-way travel time multiplied by two, or $2{*}dt_p(t_d)$. Using Equation 2, the calculation results of $N_p(t_d)$ can be seen in Table 40.

Table 40. Number of trucks required to transport goods from the Port of Biu and Tardamu Airport to the Port of Seba following the Seroja tropical cyclone incident

Port/airport	**Daily available spare capacity (DWT) ($SC_p(t_d)$)**	**Average round trip travel time in hours ($2{*}dt_p(t_d)$)**	**Number of trucks* needed to capture the port spare capacity per day ($N_p(t_d)$)**
Biu	290	2.6	3 (-2 trucks)
Tardamu (airport)	110	Road access is not passable	-

Based on the disaster impact analysis results on port-hinterland network connectivity in Sabu Island, we found two significant changes compared to the normal situation. The first change is the reduction of the number of trucks needed to capture spare capacity at the Port of Biu. Note that this change in resource needs was not caused by better hinterland access but by reduced spare capacity at the Port of Biu due to the tropical cyclone. Meanwhile, the access road to Tardamu Port at point t_d was flooded and covered with scattered debris, making it inaccessible to trucks. As a result of the closed road access, the spare capacity available at Tardamu Airport was unusable. As a result, the Port of Seba has only 290 DWT of spare capacity, corresponding to 20% of the port's overall capacity needs. In other words, due to tropical cyclone Seroja, Sabu Island lost at least 80% of the total capacity of ships visiting the Port of Seba under normal conditions.

5.3.3 Disaster Impact Analysis on Sabu Island's Shipping Network Connectivity

In this section, we analyze the changes in shipping network connectivity on Sabu Island due to operational disruptions at the Port of Seba. To analyze the changes in shipping connectivity on Sabu Island, we faced the challenge of data that is difficult to obtain through public sources, such as AIS. The ports on Sabu Island are very small and there is no AIS service covering these ports. In addition, the data retrieved from SIMLALA does not include route adaptation data from ships when a port is disrupted; it only includes voyage planning approval data. To overcome this issue, internal data from the Ministry of Transportation, through the Directorate General of Sea Transportation, was used to discover the realization of port calls from all ports in Sabu Island after being affected by tropical cyclone Seroja. We obtained data on subsidized and private vessel ship visits until December 2021. The data we obtained covers 29 cargo ships and Ro-Ro vessels, which connect Sabu Island with other islands in the archipelago.

To analyze the changes in connectivity after the Port of Seba was disrupted by tropical cyclone Seroja, we used two timeframes in the resilience curve of the Port of Seba (see Figure 45). The first timeframe is response phase 1 from t_e to t_{s1}. The second timeframe is response phase 2 at duration t_{s1} to t_{f2}. Based on the data we received from the official Ministry of Transportation through the Directorate General of Sea Transportation regarding the route changes of ships in the two periods, we then compared the connectivity of the Port on Sabu Island in the two periods with the conditions during normal times as shown in Table 41 and Table 42, respectively.

Table 41. The connectivity of ports on Sabu Island during [t_e, t_{s1}] compared to the daily average of normal conditions in 2018 before the disaster

Rank	Port	Port connectivity (in DWT)	Average connectivity per day (DWT/day)	Change of connectivity per day (%)
1	Biu	27,482	1,042	+535 (+105%)
2	Tardamu (airport)	3,068	118	+118 (-)
3	Seba	0	0	-1448 (-100%)
Sabu Island's connectivity		**30,550**	**1,160**	**-795 (-40%)**

The results of the data analysis in Table 41 shows that the total closure of the port of Seba reduced the connectivity of Sabu Island by approximately 40% from its normal condition. Ships could only use the port of Biu as it is the only alternative seaport for loading and unloading cargo. During this timeframe, the Port of Biu experienced an increase in traffic of 105% compared to normal conditions, which absorbed 38% of the normal traffic at the Port of Seba. Meanwhile, Meanwhile, the Tardamu airport was open for small cargo planes, but passenger traffic was temporarily on hold. Tardamu Airport could support the loading and unloading around 118 DWT of cargo per day, which can help serve around 5% of the Port of Seba's demand during normal times.

Table 42 shows the analysis results for timeframe 2. Timeframe 2 was when the Port of Seba was partially opened, considering that stevedores and all port operational personnel could work again. However, with MV Cantika Lestari 10C still stranded at its main berth, the berthing facilities that the vessel could use for loading and unloading were still limited. Due to the limited berths for loading and unloading, the size of vessels entering and leaving Seba Port was also very limited. At the end of timeframe 2, traffic at the Port of Seba had returned to normal.

Table 42. The connectivity of cargo ports in Seba Island during timeframe 2 [t_{s1}, t_{f2}] compared to the average normal conditions in 2020 - 2021 before the disaster

Rank	Port	Port connectivity (in DWT)	Average connectivity per day (DWT/day)	Change of connectivity per day (%)
1	Biu	226,164	1,203	+696 (+137%)
2	Seba	68,620	365	-1083 (-75%)
3	Tardamu (airport)	16,920	90	+90 (-)
Sabu Island's connectivity		**264,516**	**1,512**	**-443 (-23%)**

From the analysis of timeframe 2, we found an increase in traffic at the Port of Biu, from an average daily connectivity of 1,057 DWT during response phase 1 to 1,203 DWT during response phase 2. The increase was due to the movement of operational workers from the port of Seba in the west to the port of Biu in the east. With the increasing speed of loading and unloading cargo at the Port of Biu, ships began to switch to the port more frequently. In addition, the short distance between the western and eastern parts of Sabu Island makes the Port of Biu an effective alternative for loading and unloading goods on Sabu Island.

In addition to analyzing the dynamics of the port and airport on Sabu Island, we also analyzed the dynamics of shipping services that represent the edges of the maritime shipping network for Sabu Island. Our analysis is limited to changes in shipping services for ships serving the Port of Seba and how these ships react to operational disruptions due to tropical cyclone Seroja. Reactions fall into one of four categories: reroute (when ships sail to other ports that were not previously on a fixed schedule), skip (when ships sail directly to the next port on their scheduled route without adding a new port destination), cancel (when a schedule is completely canceled), or no change (when there is no change at all from an original schedule).

Table 43. Analysis shipping services responses after the closure of Port of Seba during timeframe 1 $[t_d, t_{s1}]$

Initial inbound trajectory	**Response link**	**% Estimation of diverted shipping capacity (in DWT)**	**Type of response**
Ambon - Seba	Ambon – Tenau/Kupang Ambon – Biu	75% 25%	Rerouting Rerouting
Biringkassi - Seba	Biringkassi – Biu	100%	Skipping
Bitung - Seba	Bitung – Tenau/Kupang Bitung – Biu	45% 55%	Rerouting Rerouting
Biu - Seba	-	-	Cancelling
Ende/Ippi - Seba	Ende/Ippi – Biu	100%	Rerouting
Labuan Bajo - Seba	Labuan Bajo – Raijua	100%	Rerouting
Makassar - Seba	Makassar – Tenau/Kupang	100%	Rerouting
Maumbawa - Seba	Maumbawa – Raijua	100%	Rerouting
Merauke - Seba	Merauke – Tenau/Kupang	100%	Rerouting
Ndao Baa - Seba	Ndao Baa - Biu	100%	Rerouting
Ndao Ndao - Seba	Ndao Ndao - Biu	100%	Rerouting
P. Ende - Seba	P. Ende - Raijua P. Ende – Biu	35% 65%	Rerouting Skipping
Raijua - Seba	Raijua – Biu	30% 70%	Skipping Rerouting
Reo - Seba	Reo - Biu	33% 67%	Skipping Rerouting
Samarinda - Seba	Samarinda – Tenau/Kupang	100%	Rerouting
Sampit - Seba	-	-	Cancelling

Initial inbound trajectory	Response link	% Estimation of diverted shipping capacity (in DWT)	Type of response
Sangkulinang - Seba	Sangkulinang – Raijua	100%	Rerouting
Sape - Seba	Sape – Raijua	100%	Rerouting
Sorong - Seba	Sorong – Tenau/Kupang	100%	Rerouting
Tanjung Buton - Seba	-	-	Cancelling
Tanjung Perak - Seba	Tanjung Perak – Tenau/Kupang	100%	Rerouting
Tenau/Kupang - Seba	Tenau/Kupang - Biu	20%	Rerouting
	Tenau/Kupang - Tardamu	70%	Rerouting
	Tenau/Kupang - Raijua	10%	Skipping
Waikelo - Seba	Waikelo – Raijua	100%	Rerouting
Waingapu - Seba	Waingapu – Raijua	100%	Rerouting
Waren - Seba	Waren - Raijua	100%	Rerouting

Based on our results in Table 43, during response phase 1, where the Port of Seba was temporarily closed and did not service ships at all, we found that most ship services were skipped or rerouted to the Port of Biu as a substitute for not being able to visit the Port of Seba. This was generally done by small ships with the characteristics of a "*short hop route*." Meanwhile, medium-sized vessels with direct (long-distance) routes from the western Indonesia region chose Raijua Port as an alternative route. Goods from Raijua Port were consolidated and sent using small short-hop route ships from Raijua Port to Biu Port on Sabu Island. Meanwhile, large ships that could not call directly at the Port of Biu chose Tenau/Kupang Port as a consolidation port. Most goods consolidated at this port were sent by air to Tardamu Airport on Seba Island. The rest was sent using ships with smaller sizes that rerouted to Biu Port, or medium or large-size ships that directly anchored to Raijua Port to avoid congestion of ship flow at Biu Port.

The results of the edge analysis on shipping connectivity during response phase 2 can be seen in Table 44. Timeframe 2 starts when the Port of Seba had partially reopened its operations, marked by the recovery of operational workforce capacity. However, operations during this period could not be fully opened due to MV Cantika Lestari 10C, which was still stranded at the main berth of the Port of Seba. In the analysis in this section, we added one more type of response, namely 'returning,' which means that shipping services in that section returned to using the Port of Seba as before. The type of response was based on the comparison between response phase 1 and 2.

We found that during response phase 2, medium-sized cargo vessels from the western part of Indonesia redirected their vessels to the Port of Seba (from previously skipping or rerouting to Raijua Port) despite the limited berth capacity at the port. This is because UPP Class III Seba prioritized vessels transporting important goods from the western part of

Indonesia, namely Java Island, to Sabu. The remaining capacity at the Port of Seba was focused on handling these vessels to keep the supply of cargo or commodities on time and on remaining efficient. Small vessels using hop-short routes in the region showed no significant change (unchanged) by continuing to use the Port of Biu as an alternative to avoid congestion at Seba Port, which was filled with medium-sized cargo ships carrying goods from the West of Indonesia. Another interesting thing to observe is the change in the proportion of consolidated shipments at Tenau/Kupang Port. At this port, there was a decrease in air freight shipments as some cargo (generally those carrying critical commodities for Sabu Island) could now be sent directly to the Port of Seba. The shipment of goods consolidated at Tenau/Kupang Port was still dominated by ships unloading goods at the Port of Biu.

Table 44. Edge analysis of the response from shipping services connected to the Port of Seba during timeframe 2 $[t_{f1}, t_{s2}]$

Initial inbound trajectory	Response link	% Estimation of diverted shipping capacity (in DWT)	Type of response
Ambon - Seba	Ambon – Tenau/Kupang	75%	Unchanged
	Ambon – Biu	25%	Unchanged
Biringkassi - Seba	Biringkassi – Biu	0%	-
	Biringkassi - Seba	100%	Returning
Bitung - Seba	Bitung – Tenau/Kupang	45%	Unchanged
	Bitung – Biu	55%	Unchanged
Biu - Seba	-	-	Cancelling
Ende/Ippi - Seba	Ende/Ippi – Biu	100%	Unchanged
Labuan Bajo - Seba	Labuan Bajo – Raijua	-	-
	Labuan Bajo - Seba	100%	Returning
Makassar - Seba	Makassar – Tenau/Kupang	100%	Unchanged
Maumbawa - Seba	Maumbawa – Raijua	0%	-
	Maumbawa - Seba	100%	Returning
Merauke - Seba	Merauke – Tenau/Kupang	100%	Unchanged
Ndao Baa - Seba	Ndao Baa - Biu	100%	Unchanged
Ndao Ndao - Seba	Ndao Ndao - Biu	100%	Unchanged
P. Ende - Seba	P. Ende - Raijua	35%	Unchanged
	P. Ende – Biu	65%	Unchanged
Raijua - Seba	Raijua – Biu	30%	Unchanged
		70%	Unchanged
Reo - Seba	Reo - Biu	33%	Unchanged
		67%	Unchanged
Samarinda - Seba	Samarinda – Tenau/Kupang	100%	Rerouting
Sampit - Seba	-	-	Cancelling

Initial inbound trajectory	Response link	% Estimation of diverted shipping capacity (in DWT)	Type of response
Sangkulinang - Seba	Sangkulinang – Raijua	0%	Rerouting
	Sangkulinang - Seba	100%	Returning
Sape - Seba	Sape – Raijua	100%	Rerouting
Sorong - Seba	Sorong – Tenau/Kupang	100%	Rerouting
Tanjung Buton - Seba	-	-	Cancelling
Tanjung Perak - Seba	Tanjung Perak – Tenau/Kupang	0%	-
	Tanjung Perak - Seba	100%	Returning
Tenau/Kupang - Seba	Tenau/Kupang - Biu	60%	Rerouting
	Tenau/Kupang - Tardamu	25%	Rerouting
	Tenau/Kupang – Seba	15%	Returning
Waikelo - Seba	Waikelo – Raijua	0%	-
	Waikelo - Seba	100%	Returning
Waingapu - Seba	Waingapu – Raijua	0%	-
	Waingapu - Seba	100%	Returning
Waren - Seba	Waren - Raijua	0%	-
	Waren - Seba	100%	Returning

5.4 Phase 4: Resilience Intervention Analysis

In this section, we describe the various interventions and the actors who delivered these interventions to improve the resilience at Seba Port. The interventions analyzed in this section include port-level interventions (L1) and island transportation network-level interventions (L2). The analysis in this section uses qualitative content analysis and interviews as the main techniques to find out what resilience interventions were taking place. Twenty-six mass media articles and interviews with three experts from the port authority at the Port of Seba were used as primary sources to conduct resilience intervention analysis.

As for the data obtained, each intervention will be grouped based on the time it was taken, whether in the preparation phase ($t < t_e$), response phase ([t_d, t_s] or [t_e, t_s]), recovery phase [t_s, t_f], or adaptation phase ($t > t_f$). In each phase of the resilience cycle, the interventions will be sorted based on when the intervention was taken. Other information added for each intervention includes the type of theoretical category, actors involved in decision-making, and whether the intervention category belongs to the L1 (port) or L2 (island) category. In the next subsection, we will explain the resilience interventions carried out in each phase of the resilience cycle in more detail.

5.4.1 Resilience Intervention Analysis in the Preparation Phase ($t < t_e$)

This subsection describes the resilience interventions taken before the disaster (preparation phase or period $t < t_e$ on the resilience curve). A list of all interventions taken in the preparation phase is shown in Table 45. The table lists all port resilience interventions, when the intervention happened, theoretical intervention categories, and port stakeholders involved. Each resilience intervention also indicates whether the intervention is at the port (L1) or network (L2) level.

Based on the data that has been processed, it was found that there were seven resilience interventions in the Port of Seba in the preparation phase. Of the seven interventions, six focused on process preparedness, while one focused on the infrastructure. UPP Class III Seba and BMKG East Nusa Tenggara initiated cooperation to facilitate coordination and exchange information for preparing for extreme events such as tropical cyclones. The initiation of this collaboration started in the beginning of 2018.

The results of this collaboration made it easier for UPP Class III Seba to identify tropical cyclone seeds. One of the seeds identified by BMKG was formed on April 2, 2021, or 2 days before the formation of tropical cyclone Seroja. BMKG did not warn the UPP Class III Seba about the tropical cyclone at that time, because the seedling had not shown strong signs of becoming a large-scale tropical cyclone. The tropical cyclone seedlings grew 12 hours later on April 3, 2021. At this time, BMKG East Nusa Tenggara notified UPP Class III Seba that there might be a tropical cyclone with a speed of over 100 km/hour that might cross the Port of Seba.

Shortly after receiving notification from BMKG East Nusa Tenggara regarding the tropical cyclone that might pass, UPP Class III Seba examined the possible trajectory of this tropical cyclone to estimate what preparations were needed before the tropical cyclone would pass. Considering the potential for tropical cyclones that pass through the port was quite large, UPP Class III Seba took the initiative to warn inland trucks at the Port of Seba to immediately leave the port area and head to eastern Seba, which is relatively projected for the tropical cyclone.

In addition, the port also closed access to Inland truck arrivals heading to the Port for security reasons. During this time, UPP Class III Seba and several operational workers moved goods in the stacking field to be put into the warehouse to protect the goods better. The warehouse at the Port of Seba at that time was designed to have excess capacity to anticipate the soaring demand for goods on Sabu Island. This excess warehouse capacity was used in this case to store goods and general cargo from the stacking field. This goods transfer was the only intervention that focused on physical infrastructure in preparation for the arrival of tropical cyclone Seroja.

On April 3, 2021, UPP Class III Seba still decided to serve anchored ships. At that time, MV Cantika Lestari 10C requested permission to dock after arriving late from the port of origin. Then UPP Class III warned MV Cantika Lestari 10C to delay departure to the next destination, the Port of Raijua, because there would potentially be a tropical cyclone, and access for inland trucks had been restricted to the Port of Seba. Another intervention carried out by UPP Class III Port of Seba was to plan a rotation for UPP Class III Port Seba officers and also stevedoring workers, especially those living in the western Sabu area, which at that time was projected to be passed by tropical cyclone Seroja. The hope was that this rotation of officers would keep the Seba Port operations running even when it would be affected by the tropical cyclone.

Table 45. Resilience interventions during the preparation phase ($t < t_e$). For the intervention category. Hard = Hardening, Red = Redundancy, Mod = Modularity, CT = Capacity Tolerance, PT = Personnel Training, RP = Response Planning, Coord = Coordination, Coop = Cooperation

No	Resilience interventions and level category	Specific Time taken (*Period* $t < t_e$)	Category								Actors involved
			Infrastructure Preparedness				Process Preparedness				
			Hard	**Red**	**Mod**	**CT**	**PT**	**RP**	**Coord**	**Coop**	
1	UPP Class III of Port of Seba always maintains close contact with the BMKG to exchange climate information on East Nusa Tenggara because the area is prone to disasters. (L1)	Close contact initiated since early 2018							√		UPP Class III Seba & BMKG
2	Request tropical cyclone forecast information to BMKG and request information on tropical cyclone potential. (L1)	~ 48 hours before tropical cyclone Seroja* (2 April 2021)							√		UPP Class III Seba and BMKG
3	Study the forecast to know the trajectory of Tropical Cyclone Seroja. (L1)	~ 30 hours before the occurrence of tropical cyclone Seroja (3 April 2021)						√			UPP Class III Seba
4	Put the goods outside the warehouse into the warehouse (according to the remaining capacity). (L1)	~ 18 hours before tropical cyclone Seroja (April 3, 2021)				√					UPP Class III Seba, Stevedoring Labor
5	UPP Class III Seba suggests transport trucks at the Port of Seba immediately leave the port and head to the eastern region of Sabu Island. (L1)	~ 14 hours before tropical cyclone Seroja (April 3, 2021)							√		UPP Class III Seba, inland truck driver
6	Warn Slow-Moving vessels to delay departure to anticipate the impact of Tropical Cyclone Seroja. (L1)	~10 hours before tropical cyclone Seroja (April 3, 2021)							√		UPP Class III Seba, Ships Crew
7	Make a human resource scheduling plan after tropical cyclone Seroja by considering the residence of human resource personnel. (L1)	~8 – 10 hours before tropical cyclone Seroja (3-4 April 2021)						√			UPP Class III Seba

5.4.2 Resilience Intervention Analysis during Response Phase [t_e, t_s]

This subsection discusses resilience interventions in the response phase for the tropical cyclone. This Response Phase analysis period begins on April 4, 2021 (point t_e), when tropical cyclone Seroja hit, until November 23, 2021 (point t_{s2}), after the successful evacuation of MV Cantika Lestari 10C. Point t_e was selected as a starting point because of the nature of tropical cyclones, a type of natural incident that can be forecasted and lasts long. This nature allowed the UPP Class III Seba to reduce the impact of this tropical cyclone on the port, even though tropical cyclone Seroja was still ongoing.

The total duration of this response phase was 233 days, which is divided into two parts. Response phase 1 lasted for 27 days from April 4, 2021 to May 1, 2021 (point t_{s1}), when the Port of Seba was opened because the port capacity had been partially recovered due to the availability of stevedoring labor. At this t_{s1} point, MV Cantika Lestari 10C was still stranded at the dock and had not yet been removed. Meanwhile, response phase 2 lasted for 206 days from May 1, 2021 (point t_{s1}) to November 23, 2021 (point t_{s2}), when the wreck of MV Cantika Lestari 10C was completely removed, and the berth capacity at the Port of Seba could be fully utilized again. Table 46 and Table 47 list the resilience intervention in response phase 1 and 2, respectively.

In response phase 1, the first intervention was that UPP Class III Seba formed a small team responsible for responding to disasters, called the Emergency Response Team (ERT). The ERT of Port of Seba focused on coordinating spare capacity from alternative ports and airports on Sabu Island to be used temporarily to replace the capacity of the Port of Seba. This intervention aimed to prevent Sabu Island from becoming isolated for loading and unloading goods. The concern that Seba Island would be isolated is based on two reasons.

The first reason is that after the ERT made an initial assessment of the impact conditions of the tropical cyclone in the port of Seba, it was concluded that the MV Cantika Lestari 10C removal could not be done immediately. This conclusion was due to the limited expertise and technology on Seba Island to conduct the removal. Following up on the assessment results, UPP Class III Seba Port declared that the port was temporarily closed and did not serve loading and unloading services on Sabu Island. Thus, there were initial concerns about the possibility of a prolonged closure of the port of Seba.

The second reason is that due to the increasing strength of the tropical cyclone to the southwest of Sabu Island, the Central Government of the Republic of Indonesia, through the Ministry of Transportation, issued a shipping edict numbered 44/PHBL/2021 which urged shipping businesses in the East Nusa Tenggara region to be cautious for the next seven days. This shipping edict made many East Nusa Tenggara regional ships postpone shipping departures until the tropical cyclone status returned to safety. The impact of this mandate was that ERT of Port of Seba experienced limitations in bringing in the resources needed to evacuate MV Cantika Lestari 10C and repair damage at the Port of Seba. The ERT shifted its strategy by communicating with the Port of Biu operator and Tardamu Airport Management to provide spare capacity to avoid Sabu Island's isolation due to the Port of Seba’s closure. The results of this meeting led to the opening of the Port of Biu and Tardamu Airport as an alternative for shipping goods to Sabu Island after the end of tropical cyclone Seroja on April 12, 2021.

After UPP Class III Seba coordinated alternative shipping routes to Seba Island via the Port of Biu and Tardamu Airport, the next thing they did was try to repair the Port of Seba and the access road to the port, which was flooded and covered with debris due to tropical cyclone Seroja. To deal with MV Cantika Lestari 10C stranded at the Port of Seba berth, the UPP Class III Seba tried to contact the company that owns the ship in Ambon, Maluku, to remove the ship as soon as possible. Since April 14, 2021, a formal letter asked to discuss the recovery solutions. Based on information from UPP Class III Seba, the ship owner asked for time to consider removing the ship. The shipowner planned to send an expert through Tardamu Airport to assess the condition of the stranded MV Cantika Lestari 10C and to determine what resources would be needed to remove the ship. The shipowner promised to send experts after restoring the access road connecting the airport to the Port of Seba.

On April 15, 2021, UPP Class III Seba and the NTT Provincial PUPR Office cleaned up the debris covering the main access from Tardamu Airport and the Port of Seba. The Route 2 road that connects the port of Seba and Tardamu Airport was finally accessible again on April 20, 2021. On that date, the PUPR office of East Nusa Tenggara Province also announced to the mass media that Route 2 had been cleaned so that the flow of humanitarian assistance from Tardamu Airport to the West Sabu region could be carried out more massively. On April 25, 2021, UPP Class III Seba issued an order through a formal letter to the owner of MV Cantika Lestari 10C to remove the stranded wreck immediately from the Port of Seba. With the human resources that are needed to carry out port operations being available again, and the access road to the Port of Seba open, UPP Class III Seba announced that the port was reopened with a limited capacity to receive loading and unloading of ships carrying essential commodities for Sabu Island on May 1, 2021.

In response phase 2, the resilience intervention focused on evacuating the MV Cantika Lestari 10C wreck, which was stranded and covered the main berth of the Port of Seba. UPP Class III Seba sent a letter for the third time to the company that owns the ship on June 8, 2021, to think about how to remove the ship. The limited equipment and expertise to move the ship were barriers to UPP Class III Seba carrying out the removal independently, thus demanding responsibility from the shipowning company. The lengthy process of evacuating the wreck of MV Cantika Lestari 10C had also become a concern for the central government and members of the Regional Representatives Council (DPRD) in East Nusa Tenggara Province because the loading and unloading of goods at the Port of Seba became slower and caused commodity prices to rise. The Port of Biu and Tardamu Airport as alternatives were insufficient to replace the function of the Port of Seba because the alternative could only replace 50% of the capacity of the Port of Seba. UPP Class III Seba also tried to contact and request the Central Government to assist in the MV Cantika Lestari 10C shipwreck removal process. UPP Class III Seba and the NTT Transportation Office then stated to the press that dismantling and evacuating MV Cantika 10C was still in process.

In July 2021, both the Ministry of Transportation and the company that owns MV Cantika Lestari 10C responded to this request for assistance. The Indonesian Ministry of Transportation stated that the request could not be realized shortly due to the absence of a budget for removal. One factor hindering budget approval was the increased transmission rate of the Delta variant of COVID-19 in Jakarta, which jumped so high that the state budget needed to refocus on handling the pandemic. The central government on June 29, 2021, imposed a Policy on the Implementation of Restrictions on Community Activities (PPKM) as a pandemic control strategy, which also hampered the response from the central government to assist in handling the evacuation of the MV Cantika Lestari 10C shipwreck. Meanwhile, the response from the company that owns MV Cantika Lestari 10C stated that the evacuation process of MV Cantika Lestari 10C still needed to wait due to the increase in Delta-variant COVID-19 cases and the company was still looking for experts and gathering the resources needed to carry out the removal. The unexpected surge in Delta variant COVID-19 cases halted the handling of the stranded ship removal in July and August 2021.

In early September 2021, the Delta variant of the COVID-19 outbreak began to subside, including in the Sabu Island area. On September 2, 2021, UPP Class III Seba warned the company that owns MV Cantika Lestari 10C. This warning stated that if the company did not show intentions and efforts to evacuate MV Cantika Lestari 10C, then UPP Class III Seba would bring this matter to law enforcement. As a follow-up to this warning, on September 15, 2021, the company that owns MV Cantika Lestari 10C sent the first evacuation team to lift the sunken ship. Over two days, the sunken ship was partially lifted, but it was not yet in a perfect position for removal. On October 18, 2021, the company came again with a second team to start lifting the ship's sunken part. However, after three days, the sunken part could not be lifted because it was too heavy to lift. The company admitted that it lacked technical expertise in the shipwreck removal and requested additional time to lift the ship.

Finally, on November 5, 2021, the company brought in a third removal team based on recommendations from UPP Class III Seba and the NTT Transportation Office, which have special expertise in the removal of shipwrecks. Over a preiod of two days, the entire body of the sunken MV Cantika Lestari 10C was finally lifted. Although it had been lifted, the wreck still had to wait for the transport ship. MV Cantika Lestari 10C could finally be moved on November 23, 2021, and left the Port of Seba to be taken to a shipyard in the East Java area.

Table 46. Port resilience intervention during response phase 1 [t_e, t_{s1}]. For the intervention category. Repu = Repurposing, Reloc = Relocation, Repa = Reparation, Recon = Reconstruction, OF = Operational Flexibility, OA = Organizational Agility

No	**Resilience interventions and level category**	**Time taken** $[t_e - t_{s1}]$	**Category**						**Actors involved**
			Infrastructure adaptation				**Process adaptation**		
			Repu	**Reloc**	**Repa**	**Recon**	**OF**	**OA**	
1	UPP Class III Port of Seba formed a team responsible for mitigating the impact of tropical cyclone Seroja, the Emergency Response Team (ERT). The task of this team also included conducting an initial assessment of the condition of the Port of Seba. (L1)	~8 hours after tropical cyclone Seroja hit the Port of Seba (5 April 2021)						√	UPP Class III Seba
2	UPP Class III Seba declared that the Port of Seba was closed until an unspecified date. (L1)	5-Apr-21					√		UPP Class III Seba
3	The Ministry of Transportation (Central Government) issued shipping edict number 44/PHBL/2021 regarding the alert of extreme weather hazards (tropical cyclones) for the next seven days in the East Nusa Tenggara region. (L2)	6-Apr-21					√		Ministry of Transportation Republic of Indonesia; BMKG
4	UPP Class III Seba implemented a response plan to rotate duty officers at the Port of Seba based on assessing employees and the workforce affected by tropical cyclone Seroja.	6-Apr-21					√		UPP Class III Seba
5	UPP Class III Seba contacted the operator of Port of Biu to be prepared as an alternative port for loading and unloading goods on Sabu Island. (L2)	7-Apr-21						√	UPP Class III Seba
6	UPP Class III Seba contacted the Tardamu Airport Management to provide the condition of the Port of Seba and the possibility of opening the Tardamu Airport to become an alternative for loading and unloading goods for Sabu Island. (L2)	7-Apr-21						√	UPP Class III Seba, Tardamu Airport Management
7	UPP Class III Seba Emergency Response Team released an official report to the Directorate General of Sea Transportation regarding the situation at the Port of Seba and requested the mobilization of resources to assist in the port's recovery process. (L1)	8-Apr-21						√	UPP Class III Seba

Table 46 continued

No	Resilience interventions and level category	Time taken $[t_e - t_{s1}]$	Category						Actors involved
			Infrastructure adaptation				Process adaptation		
			Repu	Reloc	Repa	Recon	OF	OA	
8	Tardamu Airport was opened specifically to receive humanitarian aid and cargo shipments to Sabu Island from airports in Kupang City, the capital city of East Nusa Tenggara (NTT). (L2)	10-Apr-21						√	UPP Class III Seba, Tardamu Airport Management
9	In collaboration with the East Nusa Tenggara Transportation Agency, UPP Class III Seba cleared debris scattered in the Port of Seba area. (L1)	12-Apr-21			√			√	UPP Class III Seba, NTT Transportation Office
10	UPP Class III Seba contacted the owner of MV Cantika Lestari 10C to discuss the stranded vessel at the Port of Seba and the strategy to evacuate the vessel. (L1)	14-Apr-21						√	UPP Class III Seba
11	UPP Class III Seba announced that the Port of Biu was open and ready to be used as an alternative for loading and unloading cargo on Sabu Island. (L2)	16-Apr-21					√		UPP Class III Seba; NTT Transportation Office
12	The Ministry of Public Works and Housing (PUPR) Office in NTT completed the repair of the access road to the Port of Seba from Tardamu Airport (Route 2) and provided a situation update to the mass media. (L2)	20-Apr-21			√				The Ministry of Public Works and Housing (PUPR) Office in NTT
13	UPP Class III Seba sent a formal letter to the owner of MV Cantika Lestari 10C to discuss the evacuation process of MV Cantika Lestari 10C, which covered the main berth of the Port of Seba. (L1)	25-Apr-21					√		UPP Class III Seba
14	UPP Class III Seba decided to reopen the operations of the Port of Seba for regular cargo vessels (non-humanitarian aid) with limited capacity. (L1)	1-May-21					√		UPP Class III Seba

Table 47. Resilience intervention during response phase 2 [t_{s1}, t_{s2}]. For the intervention category. Repu = Repurposing, Reloc = Relocation, Repa = Reparation, Recon = Reconstruction, OF = Operational Flexibility, OA = Organizational Agility

No	Resilience interventions and level category	Time taken $[t_{s1} - t_{s2}]$	Category						Actors involved
			Infrastructure adaptation				Process adaptation		
			Repu	Reloc	Repa	Recon	OF	OA	
1	UPP Class III Seba sent a third letter to the company that owns MV Cantika Lestari 10C, which was stranded at the berth, to discuss the strategy and timeline for evacuating the ship. (L1)	8-Jun-21						√	UPP Class III Seba, Shipping company
2	UPP Class III Seba requested assistance while updating the situation on existing conditions at the Port of Seba to the Ministry of Transportation of the Republic of Indonesia. (L1)	14-Jun-21						√	UPP Class III Seba, Ministry of Transport Republic of Indonesia
3	UPP Class III Seba sent a legal warning letter (subpoena) to the company that owns the MV Cantika Lestari 10C, which was stranded at the Port of Seba berth. (L1)	2-Sept-2021						√	UPP Class III Seba, Shipping company
4	The company that owns MV Cantika Lestari 10C sent the first evacuation team to evacuate the ship, which had begun to sink at the Port of Seba berth. (L1)	15-Sept-2021			√				Shipping company
5	The company that owns MV Cantika Lestari 10C sent the second evacuation team to try to lift the ship's body, which was still sinking because that part was relatively heavy compared to the other parts. (L1)	18-Oct-2021			√				Shipping company
6	The owner company of MV Cantika Lestari 10C sent a third-party evacuation team to lift the entire ship's body, which it had previously failed to do so. (L1)	5-Nov-2021			√				Shipping company
7	The company that owns MV Cantika Lestari 10C moved the wreck from Seba Port to a port in East Java. (L1)	23-Nov-2021		√					Shipping company

5.4.3 Resilience Intervention Analysis during the Recovery Phase [t_{s2}, t_{f2}]

This subsection analyzes the resilience interventions taken during the recovery phase [t_{s2}, t_{f2}]. This period lasted from November 23, 2021, when the capacity of the Port of Seba fully returned due to MV Cantika Lestari 10C being successfully evacuated (t_{s2}), until December 22, 2021, when the traffic performance at the Port of Seba returned to what it was before tropical cyclone Seroja (t_{f2}), which is calculated using Cargo Vessel Capacity, CVC_{Cargo}, in DWT units. The total duration of this recovery phase was 29 days.

In this phase, the resilience intervention made by UPP Class III Seba was to provide reports to the Ministry of Transportation and press releases related to the Port of Seba, whose cargo loading and unloading capacity had fully recovered. The development of this situation then made large ships previously anchored at the Port of Tenau/Kupang and medium-sized ships that used the Port of Raijua return to the Port of Seba as a place of loading and unloading to Sabu Island. It took about a month (29 days) to restore traffic. The alternative port, Biu, was not economically viable for continuing to serve the load because it is very congested. Meanwhile, Tardamu Airport, as of December 1, 2021, had switched functions again to carry passengers. The lack of alternative ports for loading and unloading at Sabu Island made traffic to the Port of Seba return quickly because ships did not have choices for alternative ports.

5.4.4 Resilience Intervention Analysis during the Adaptation Phase ($t > t_{f2}$)

This subsection discusses the resilience intervention analysis taken during the adaptation phase. The adaptation phase is the period that begins after traffic performance at the Port of Seba returns to normal ($t > t_{f2}$), which is after December 22, 2021. The adaptation phase is useful to study whether a port takes additional resilience interventions to adapt from past events so that the Port of Seba will be ready to face future disasters similar to this tropical cyclone Seroja incident.

After the return of traffic performance at the Port of Seba on December 22, 2021, UPP Class III Seba provided a post-event review report document regarding the current situation at the Port of Seba to the Ministry of Transportation in Jakarta. One thing emphasized in the report is the need to repair the berth hit by MV Cantika Lestari 10C, which caused some parts of the berth to break and crack even though the port can serve ships for loading and unloading cargo. In addition, to reduce the dependency on one general berth, which makes port operations vulnerable to disasters, UPP Class III Seba proposed a plan to create two additional berths to support the loading and unloading of cargo and the embarkation and disembarkation of passengers. This proposal was submitted to the Central Government through the Directorate General of Sea Transportation of the Ministry of Transportation at the end of 2021.

At the beginning of January - March 2022, the proposals received attention from the central government. The proposals align with the Ministry of Transportation 2020-2024 strategic plan as stated in strategic target SS9[19] with a key performance indicator (KPI) number

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[19] SS9 in English reads, "*Improved Transportation Services in Disaster-prone, Border, Outermost, and Remote Areas*".

20[20] (Ministry of Transportation, 2021). At the end of 2022, the Indonesian Parliament approved the budget plan. The Parliament approved the proposal, considering that the Port of Seba plays a critical role in maintaining the supply of goods and passenger flow on Sabu Island. In addition, positive economic growth on Sabu Island will potentially increase goods and passenger flows in the coming years. In April 2023, the Ministry of Transportation disbursed the budget for repairing and developing the Port of Seba with a contract value of IDR 31.79 billion. The project completion is expected to be in November or December 2023.

5.5 Lessons Learned from Empirical Findings

This section summarizes the analysis results conducted using the four-phase empirical resilience method. The summary results described in this section are lessons learned related to the three main attributes of resilience, namely robustness/vulnerability, responsiveness, and rapidity/recoverability. The discussion in this section highlights key learnings and recommendations for improving these three resilience attributes. It is important to note that these lessons learned are taken in the context of a tropical cyclone disaster. Subsection 5.5.1 discusses important lessons learned from empirical findings related to the port robustness/vulnerability attribute, which is an attribute that indicates the ability of the Port of Seba to maintain residual performance after tropical cyclone Seroja. Subsection 5.5.2 focuses on the port responsiveness attribute, which is the ability to show how responsive the Port of Seba was in restoring its operational capacity in loading and unloading goods. Subsection 5.5.3 discusses lessons learned from empirical findings related to the port rapidity/recoverability attribute, which shows how quickly Seba Port could restore port performance to what it was before the disaster. These lessons learned are expected to help the Port of Seba and other ports with similar characteristics to prepare for future tropical cyclone disasters.

5.5.1 Lessons Learned Related to Port Robustness/Vulnerability

Based on the empirical analysis results, the Port of Seba showed to have a robustness value of 0 DWT/day and a vulnerability value of 1,448 DWT/day for this disaster. Below are some lessons to be learned related to port robustness/vulnerability at the Port of Seba:

1. Coordination or information exchange between the Port of Seba and organizations that are capable of capturing weather and climate anomalies (such as the Meteorology, Climatology, and Geophysics Agency/BMKG) can help ports with limited technology at the islands to improve preparations for tropical cyclones. UPP Class III Seba's awareness of the many occurrences of tropical cyclones in the past made them take the initiative to coordinate with BMKG East Nusa Tenggara to request updates on specific information about tropical cyclones. With technological support from BMKG, UPP Class III Seba had about 48 hours to prepare and make priority decisions to increase port robustness (maintain

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[20] KPI number 20 in English reads, "*Ratio of sea transportation services in disaster-prone, border, outermost, and remote areas, based on the number of pioneer transportation routes.*"

port performance) and reduce port vulnerability (reduce the impact of tropical cyclones on technical and social components at the Port of Seba).

2. The resilience interventions taken and performance indicator metrics used to measure port robustness/vulnerability need to be aligned. In this case study, the port performance metric used to measure resilience is CVC_{Cargo}. 48 hours before tropical cyclone Seroja, UPP Class III Seba decided to prioritize interventions to reduce casualties and potential damage to cargo at the Port of Seba. Even though there were no casualties and no damage to cargo stored at the Port of Seba after the tropical cyclone, the port's robustness score was low because in this case, there was no alignment between the metrics measured and the interventions carried out.

3. Special treatment is needed for ships moored at the port during a tropical cyclone. In this case study, UPP Class III Seba had advised ships to delay their departure due to the tropical cyclone. However, there was no additional treatment to ensure that moored vessels do not capsize or hit the dock. The positive outcome of this delay was that there were no casualties among the passengers and crew of MV Cantika Lestari 10C. The disadvantage was that the ship, which had been recommended to delay departure, actually hit the dock so it could not be used for loading and unloading, which caused the port robustness to get to zero because it had to be closed.

Some recommendations for the Port of Seba and similar ports to increase port robustness or reduce port vulnerability to tropical cyclone disasters in the future are as follows:

1. Adopt technology that prevents moored vessels from stranding at the docks during tropical cyclone events. Tropical cyclones often have the power to raise ocean waves that sweep moored vessels away and strand them on the berth. For a small port like the Port of Seba, stranding a ship to the main berth is a major disruption as the port needs unavailable resources and expertise to evacuate the ships. Using relevant technology can help the Port of Seba reduce the risk of stranded ships at the dock. By avoiding stranded ships at the dock, the port's performance is expected to be maintained so that the value of the robustness of the Port of Seba can increase.

2. Reducing dependence on one berth for loading and unloading goods. As found from the empirical analysis, the stranding of MV Cantika Lestari 10C immediately paralyzed the operational activities of the Port of Seba due to the absence of an alternative berth. Building several berths or jetties is one recommendation to reduce the vulnerability of ports that only depend on one berth. Thus, if one berth is closed, the loading and unloading of ships can be carried out using another.

3. Considering the safe distance between the design of one berth and another. The stranding of MV Cantika Lestari 10C teaches that constructing two berths that are too close or connected can result in both not functioning when one of them is affected by a disaster.

This happened at the Port of Seba when MV Cantika Lestari 10C was stranded on the main berth connected to the Ro-Ro ship berth. When MV Cantika Lestari 10C was stranded, parts of the ship covered the Ro-Ro berth. As a result, UPP Class III Seba decided not to use the Ro-Ro berth for safety reasons. A safe distance between docks can minimize multi-berth impact when a moored ship is stranded at the dock.

5.5.2 Lessons Learned Related to the Port Responsiveness

Port responsiveness of the Port of Seba had a total duration of 232 days. Port responsiveness shows how quickly the Port of Seba restored its loading and unloading capacity to its original state after being affected by tropical cyclone Seroja. Port responsiveness can be divided into two phases. Port responsiveness in phase 1 was 26 days. Phase 1 shows how quickly Seba Port restored partial loading and unloading capacity until it was ready to serve ships again with limited capacity. The following are some lessons learned that can be taken from the results of the empirical analysis on port responsiveness for phase 1:

1. The establishment of the ERT helped the port respond faster to the disaster's impact. As observed in the Port of Seba, a small emergency response team was formed after the tropical cyclone subsided in the port area. This team was formed to facilitate the planning of response and recovery efforts to the disaster's impacts. This ERT is a communication bridge between the port and the central government, local government, and the private sector. In this case study, the deployed ERT also considered the condition of employees affected by the disaster to ensure that the daily ERT rotation could run smoothly.

2. Cooperation between public ports in using spare capacity when a port is affected by a disaster provides two main benefits in supporting resilience. The first benefit is to increase the resilience of the island community by avoiding total isolation of the island due to the main port being closed. The spare capacity at other alternative ports and airports was still able to receive 20% of the total capacity of the Port of Seba. The second benefit is that the affected ports can immediately focus on improving port capacity with this cooperation. This is what the ERT of the Port of Seba did, where they could focus on planning and executing the steps needed to evacuate the MV Cantika Lestari 10C without being distracted by loading and unloading requests at the Port of Seba. This proves the port-hinterland and shipping network's important role in supporting a port's resilience. It should be noted that the ports and airports on Sabu Island are all non-commercial ports managed by the Government of the Republic of Indonesia, which indicates that these solutions may not be applicable to commercial ports with a competitive market.

3. Transparency between stakeholders can help in the resumption of operations. An example is what UPP Class III Seba did when it learned that the MV Cantika Lestari 10C ship was stranded. Knowing this, UPP Class III Seba immediately contacted the Directorate General of Sea Transportation (Ditjen Hubla) to provide an update related to the current situation regarding the Port of Seba, as well as requesting the mobilization of possible resources to assist in the removal of MV Cantika Lestari 10C which was stranded at the main berth.

UPP Class III Seba was transparent that there were no technological and expert resources available to remove the ship. The central government was also transparent in stating that time was needed to mobilize resources, especially the budget, because the year was ongoing during the tropical cyclone. UPP Class III Pelabuhan Seba also contacted the company that owns MV Cantika Lestari 10C, located in Ambon, and told them transparently about what happened. Hearing the situation, the company asked for more time because it needed to send an advance team to conduct an assessment and wait for the road network connected to the Port of Seba to be repaired. Based on the transparency of information exchanged between UPP Class III Seba, the Ministry of Transportation of the Republic of Indonesia, and the Shipping Company, the Seba Port management finally decided to open the port first while thinking about how to remove the stranded MV Cantika Lestari 10C wreck.

Port responsiveness in response phase 2 had a duration of 206 days. Port responsiveness 2 begins when the loading and unloading capacity of the Port of Seba has partially recovered and the port is ready to be operated on a limited basis. Phase 2 ends when the loading and unloading capacity of the port has fully recovered. The following are some lessons learned related to the port responsiveness phase 2:

1. Subpoenas get attention of stakeholders responsible for stranded vessel evaluation, reducing the duration spent on port infrastructure restoration. This was done by UPP Class III Seba when the time given to the company to evacuate MV Cantika Lestari 10C was approaching the deadline. With the subpoena, the private company was instructed to follow up on removing the vessel wreck more quickly and seriously.

2. Port management's attention to the problems experienced by private shipping companies can speed up restoring port infrastructure. In this case study, the shipping company experienced two failures in lifting the ship’s wreck, half of which was sunk into the water. Knowing this, UPP Class III Seba showed concern by recommending various alternative service providers and experts to evacuate the wreck. This cooperation paid off in the third lifting process, thus improving port responsiveness.

3. The limited number of alternative ports and airports on Sabu Island encourage the acceleration of the Port of Seba's restoration. After the tropical cyclone, alternative ports and airports on Sabu Island could only accommodate 20% of Seba Port's capacity to receive cargo ships. The impact of the tropical cyclone on the operation of the Port of Biu and the limited capacity for loading and unloading cargo at Tardamu Airport delayed the flow of goods and increased logistics costs on Sabu Island. As a result of these delays and increases in the price of goods, the people of Sabu Island pushed for the speedy of the Port of Seba capacity through hearings at the Regional People's Representative Council (DPRD), and also through the NTT Transportation Office. This continuous pressure prompted UPP Class III Seba to repair the port more quickly after social mobility restrictions during the COVID-19 pandemic subsided at the end of August 2021. That situation shows the influence of

shipping connectivity dynamics on implementing resilience interventions at the Port of Seba.

Based on the results of lessons learned obtained from empirical data related to port responsiveness 1 and 2, we found that several recommendations can be highlighted to improve the responsiveness of the Port of Seba to tropical cyclone disasters:

1. ***Build an alternative access road that connects the Port of Seba and Tardamu Airport***. Building this alternative road section ensures that the Port of Seba and Tardamu Airport remain connected. Tardamu Airport is known to have spare capacity that can be used to load and unload cargo, as seen in this case study. However, this capacity could not be used because the only access road was closed. In addition, the shipping company responsible for the stranding of MV Cantika Lestari 10C also delayed sending assessment teams and equipment for their evacuation due to the closed access road. This shows that port-hinterland connectivity is critical to building port resilience by improving port responsiveness.

2. ***Preparing resources in the form of equipment, knowledge, and expertise to evacuate stranded vessel wrecks***. Based on the empirical data findings, it was found that one of the factors that made the evacuation of MV Cantika Lestari 10C take up to 232 days was that UPP Class III Seba lacked the resources of equipment, knowledge, and expertise to evacuate stranded vessels. A strategy that can be used to prepare for these resources is providing recommendations to private companies to prepare budgets and expertise for disaster response. Another strategy is training port management officers to deal with stranded ships at the dock.

3. ***Strengthen cooperation with wider regional elements to avoid logistical and expertise bottlenecks (set up regional partnerships).*** Although Sabu Island has only two ports and one airport, it has many ports near the Port of Seba, such as the Port of Raijua, Ndao Ndao, Ndao Baa, or Tenau/Kupang. Strengthening cooperation between ports in the region has the potential to make up for the lack of spare capacity and expertise needed to evacuate vessels, resulting in faster disaster management.

4. ***Create standard operational procedures for responding to disasters involving private assets or those not owned by the port.*** In the early days of the response phase, UPP Class III Seba requested assistance from the central government and the company that owns the Cantika Lestari 10C to remove the ship. At that time, there was still a debate regarding who should be responsible for evacuating the ship, especially when all actors involved (port management, central government, and private sector) had limited resources. In addition, there is no clear basis for the maximum time limit when a stranded vessel should be removed. Creating a procedure manual accompanied by a clear legal basis is expected to reduce the time required in disaster management.

5.5.3 Lessons Learned Related to Port Rapidity/Recoverability

The port rapidity value for this case was 29 days, and the port recoverability was 33 DWT/day. Port rapidity and port recoverability show how quickly the performance of the Port of Seba, as measured by CVC_{Cargo}, can return to normal after the port's vessel handling capacity has been fully recovered. The following are lessons learned related to port rapidity/recoverability:

1. For small public ports such as the Port of Seba, making announcements to local communities and the central government can speed up the return of vessel traffic to Seba Port. In general, the purpose of a public port is not to make a profit but to ensure that the public port can serve the people's needs. From the port manager's point of view, restoring the capacity of Seba Port to the minimum service standard is the main thing to pursue. However, UPP Class III Seba went beyond just restoring capacity. They actively informed the central government, local government, and local community media about the current situation in the Port of Seba. UPP Class III Seba immediately publicized it massively so that the government and the community knew the port was functioning again.

Based on the results of the empirical data we processed related to port rapidity/recoverability at the Port of Seba when exposed to tropical cyclone Seroja, we highlighted several points that can be used to improve the port rapidity/recoverability. Some recommendations are as follows:

1. ***Utilize multi-channel communication technology*** to update the status of the Port of Seba operations. Several online communication channels such as social media, official websites, and official mobile apps developed by the Port of Seba can update the operational status in real time.

2. ***Strengthen communication procedures between the Port management, the provincial transportation office, and the central government of the Ministry of Transportation of the Republic of Indonesia***. Smooth communication procedures between the Port of Seba, the Transportation Agency, and the Central Government can help to convey the current situation at the Port of Seba to all who need the information. Strong communication between stakeholders is expected to accelerate the return of traffic and utilization of the Port of Seba after the disaster.

5.6 Concluding Remarks and Summary

Chapter 5 described the implementation of the port resilience evaluation method at the Port of Seba, one of the smaller ports at a small island in the Indonesian Archipelago. This method was implemented when the port was affected by the Seroja tropical cyclone disaster from April 4-9, 2021. This chapter demonstrated how to apply the four phases of the port resilience evaluation method and the analysis results in each phase.

Section 5.1 demonstrated the implementation of the method in phase one, the port system and island connectivity analysis. This section discussed in detail the context of the Port of Seba and Sabu Island as the central object of analysis in this case study. The analysis results are shown in Figure 38, describing the socio-technical components that support the port of Seba's operations. In addition, this section also explains the connectivity of Sabu Island, in terms of a shipping connectivity analysis and the ports-hinterland network. The analysis found that the shipping connectivity of Sabu Island for a period of six months under normal conditions is around 351,900 DWT for goods transportation. The average ship capacity connectivity is around 1,955 DWT daily. Sabu Island maritime connectivity is supported by two ports, namely the Port of Seba and Port of Biu. The Ports of Seba and Biu support the connectivity by 75% and 25%, respectively. For ports-hinterland network connectivity, the analysis results show that alternative ports and airports other than the Port of Seba have a spare capacity of 50% of the total capacity of the Port of Seba in receiving cargo ships. In addition, for the ports-hinterland connection, the Port of Seba is connected by three land routes with Biu Port. In contrast, the connection with Tardamu Airport has only one access road connecting the Port of Seba.

Section 5.2 describes the application of the resilience evaluation method in phase two, namely resilience curve analysis. The built resilience curve includes four phases of the resilience cycle using a single performance indicator: Cargo Vessel Capacity (CVC_{Cargo}). CVC_{Cargo} shows the maximum theoretical capacity of cargo vessels visiting Seba Port within a certain period. The resilience curve can be seen in Figure 45. Based on the constructed resilience curve, the theoretical resilience attributes of the Port of Seba against tropical cyclone disasters can be calculated. The value of port robustness is 0 DWT; port vulnerability is 1,448 DWT/day; port responsiveness is 232 days; port rapidity is 29 days; and port recoverability is 33 DWT/day.

Section 5.3 described the third phase, which focuses on the impact of tropical cyclone Seroja on (1) socio-technical components at the Port of Seba and (2) connectivity of the Sabu Island transportation network, both ports-hinterland network and shipping connectivity. The biggest impact of tropical cyclone Seroja on socio-technical components was on the main berth. Two berths at the Port of Seba, both the main general cargo dock and the Ro-Ro, were affected because MV Cantika Lestari 10C crashed and was stranded at the berths. The direct impact on the ports-hinterland network was the reduction of *Daily Spare Capacity at the time* t_d *in DWT* ($SC_p(t_d)$) both at the Port of Biu (reduced by 16%) and Tardamu Airport (reduced by 5.5%).

In addition, tropical cyclone Seroja also blocked the only access road from the Port of Seba to Tardamu Airport, which made the access road impassable, and caused that the spare capacity of Tardamu Port could not be utilized for a while. Regarding the impact on shipping network connectivity on Sabu Island, we analyzed the changes during response phase 1 and 2 of the resilience cycle according to the resilience curve. During response phase 1, the Port of Biu became an alternative for small vessels to load and unload goods, while large or medium-sized vessels consolidated cargo at two ports, namely the Port of Raijua for vessels originating from western Indonesia and the Port of Tenau/Kupang for vessels originating from eastern Indonesia. The cargo consolidated at these two ports were transported by smaller vessels to the Port of Biu or Tardamu Airport, the only entry point for goods to Sabu Island. For changes in response phase 2, some medium-sized cargo ships carrying critical cargo for Sabu Island from the West started returning to the Port of Seba. Meanwhile, other small and medium ships still use the Port of Biu as an alternative entrance to Sabu Island.

Section 5.4 described the implementation of phase four of the empirical resilience analysis method, the resilience intervention analysis. The analysis in this section focused on identifying the interventions to improve port resilience in each phase of the resilience cycle. Interventions in the preparation phase can be seen in Table 45. In this phase, UPP Class III Seba focused on preparing itself to face tropical cyclone Seroja, which would pass through the Port within 48 hours based on the information from BMKG. The list of interventions carried out during the response phase can be seen in Table 46 and Table 47 for response phase 1 and 2, respectively. In response phase 1, UPP Class III Seba formed an Emergency Response Team to initiate cooperation with alternative ports and airports to prepare to receive traffic originating from Seba Port. In this response phase 1, the ERT also focused on being able to quickly reopen the Port of Seba, at least partially, to avoid the isolation of Sabu Island. In response phase 2, the intervention carried out by UPP Class III was focused on allowing the MV Cantika Lestari 10C wreck to be removed. In the recovery phase, the intervention focused on returning traffic to Seba Port because the loading and unloading capacity had returned to normal after the evacuation of MV Cantika Lestari 10C. In the adaptation phase, the intervention carried out by UPP Class III Seba focused on obtaining approval and funding from the central government and the Indonesian Parliament to build two additional docks so that the Port of Seba does not depend on only one dock to provide loading and unloading services for Sabu Island.

Finally, Section 5.5 summarized the lessons learned based on the empirical analysis of applying the resilience evaluation method and how it relates to the theoretical resilience attributes. Section 5.5 highlights the best practices and lessons learned related to the resilience attributes. In addition, this section provides recommendations for UPP Class III Seba and similar port operators to boost the value of the Port Robustness/Vulnerability, Responsiveness, and Rapidity/Recoverability attributes in case of a future disaster.

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6 Case Study: Port of Mamuju Simboro

Chapter 6 presents the results of implementing empirical evaluation methods for port resilience at the Port of Mamuju Simboro as the third case study. This case study focuses on the Port of Mamuju, affected by the Majene Earthquake on 15 January 2021[21]. This chapter analyses the Port of Mamuju, which is specifically dedicated to inter-island passenger crossings. This port was selected to test the evaluation method developed to support the resilience of inter-island passenger transport in the archipelago. Further description of the earthquake disaster can be seen in subsection 3.3.2. Furthermore, selecting this port as a case study tests the implementation of the proposed methods on a port with severely restricted access to public data. This contrasts with the data availability for the other two case studies.

This chapter is divided into six sections, each corresponding to a phase of the evaluation method. Section 6.1 describes the implementation of phase one, which involves the analysis of the Port of Mamuju as a socio-technical system, and Sulawesi Island's connectivity for passenger transport as a complex spatial network. This analysis is conducted to understand the context of the case study. Section 6.2 describes phase two by discussing the empirical resilience curve analysis based on selected key performance indicators relevant to the Port of Mamuju Simboro as a public passenger port. Section 6.3 is the implementation of phase three, which provides a detailed analysis of the impact of the Majene earthquake on the Port of Mamuju and on the connectivity of sea transportation for passengers. Section 6.4 is the implementation of phase four, which explores the interventions and strategies that were implemented at the port level (L1) and Sulawesi Island's transportation network for passengers (L2) according to the phases of the resilience cycle: preparation, response, recovery, and adaptation. Section 6.5

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[21] The datasets used in this case study are available at https://doi.org/10.4121/b11a5d06-e65a-479c-9259-456c15a16e5d

presents the synthesis and lessons learned from the empirical findings and how these lessons relate to the theoretical resilience attributes. This section also contains recommendations for port stakeholders to enhance resilience attributes based on the findings of the empirical analysis. Finally, Section 6.6 summarizes the empirical findings and concludes this chapter.

6.1 Phase 1: Port System and Island Connectivity Analysis

Section 6.1 divides the analysis into three complementary parts to fully understand the context of Mamuju Port within this case study. Subsection 6.1.1 analyses the port itself as a socio-technical system. Subsections 6.1.2 and 6.1.3 focus on external networks influencing the port's functionality. Subsection 6.1.2 examines the road network's spatial condition on Sulawesi Island, particularly its role in connecting alternative passenger ports to Mamuju Port. Subsection 6.1.3 examines the inter-island connectivity of passenger shipping services linked to the port of Mamuju. The study uses metrics developed from complex network analysis to analyze these external networks, which allow a deeper understanding of passenger shipping and port-hinterland connectivity in this case study.

6.1.1 Analysis of Port of Mamuju Simboro and Its Operations as a Socio-Technical System

In subsection 6.1.1, we describe the conditions at the Port of Mamuju in 2021, along with the technical and social components that support operations at the port. The discussion in this subsection begins by exploring the spatial position of the Port of Mamuju, its characteristics, and the facilities available at the Port. Furthermore, this subsection describes the conceptualization of the port as a socio-technical system, illustrated using a block diagram.

Overview of Mamuju Simboro Ferry Port in Sulawesi Island

Mamuju Port is situated in Mamuju Regency, West Sulawesi, at the waters of the Makassar Strait (Ministry of Transportation, 2019). Figure 53 illustrates the location of Mamuju Ferry Port. In the national port hierarchy, Mamuju Ferry Port is designated to facilitate passenger crossings, particularly between Sulawesi Island and East Kalimantan Province in Kalimantan Island. The position of Mamuju Ferry Port is regulated by Decree of the Minister of Transportation Number KP 725 of 2014 (Ministry of Transportation, 2014), which states that Mamuju Ferry Port is a port managed by PT ASDP Indonesia Ferry (Persero) Mamuju branch, a state-owned enterprise engaged in the business of integrated ferry and port services in the Indonesian archipelago.

The Mamuju Ferry port is the principal passenger port in West Sulawesi, Indonesia. It serves as the primary gateway to the Mamuju region from other islands. The operational area of the port is approximately 8,338 square meters. The port offers scheduled ferry services connecting Mamuju to Balikpapan, Panajam, and Samarinda ferry ports. According to data from the Badan Pusat Statistik (2022b), it served 64,970 passengers and 3,138 vehicles in 2021, or 178 passengers daily. The ferry vessels that operate at the Mamuju Ferry Port have an average capacity of 200-300 passengers. In addition to transporting passengers, these ferries are also designed to transport motorcycles, cars, trucks, and primary commodities.

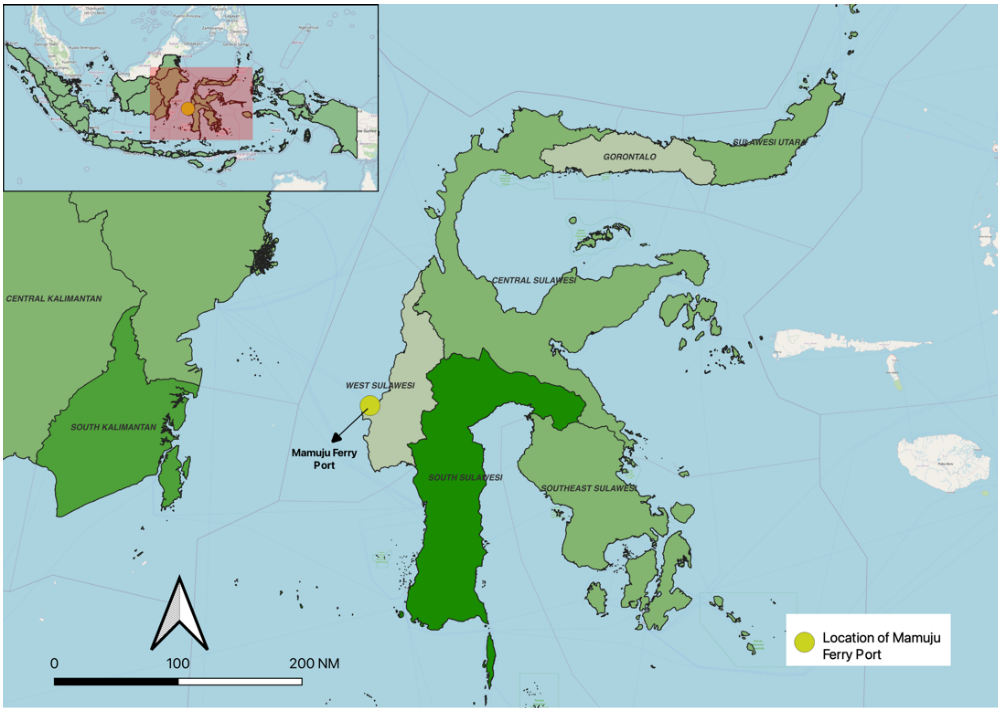

Figure 53. The location of the Mamuju Simboro Ferry Port, West Sulawesi, Indonesia (Adapted from Open Street Map)

The Mamuju Ferry Port has a single jetty designed for ro-ro vessels. This jetty is used for medium-sized ro-ro ships with a 1,000-2,000 gross tonnage (GT) capacity. There is a 2,220m^2 field used as a waiting area for vehicles that will use the Mamuju ferry port. The port has a warehouse for storing goods with an area of 234 m^2 and a capacity of up to 2,000 tons. Other supporting facilities are available, such as the port office, passenger waiting room, place of worship, toilet, parking area, and food and beverage kiosks. Table 48 provides an overview of the technical facilities available at Mamuju Ferry Port. Figure 54 presents the daily conditions of Mamuju Ferry Port in 2021 before the Majene Earthquake disaster, according to PT. ASDP Indonesia Ferry (2022).

Table 48. Existing facilities of the Port of Mamuju in 2021 (Badan Pusat Statistik, 2022)

No	Facilities	Units	Dimension
1	Berth (Ro-Ro)	m^2	60 x 10.5 = 630
2	Trestle	m^2	80 x 8 = 640
3	Vehicle waiting area	m^2	2,220
4	Warehouse	m^2	234
5	Passenger terminal	m^2	280
6	Port office	m^2	20 x 10 = 200
7	Official residential	m^2	200
8	Reservoir	m^2	24
9	Port access road (wide)	m	6
10	Electricity	Kwa	6,600
11	Parking area	m^2	1,220

Figure 54. The situation of Mamuju ferry port when closed (left) and when used for crossing (right) (Courtesy of PT. ASDP Indonesia Ferry, 2022)

To facilitate operational functions at Mamuju Port, PT ASDP Indonesia Mamuju Branch had approximately 28 employees in 2021 (Ministry of Transportation, 2022b). The human resources in this case study are those engaged in port operations and exclude those responsible for ship operations. We limit our analysis to port-based personnel because they possess considerable authority to influence resilience operations at Mamuju Ferry Port. Table 49 shows a list of social components that are directly involved in supporting the operations of Mamuju Ferry Port.

Table 49. A list of first-layer actors (social components) that support the operational aspects of the Port of Mamuju[22]

Actors	Entities	Roles	Personnel
Port operators	Management of PT. ASDP Mamuju Simboro Port Branch	Port and ferry operations officers	5
		Port and ferry maintenance officers	4
		Port operations personnel for stevedoring services and porters	20

Mamuju Simboro Ferry Port as a socio-technical system

To map the operational system of Mamuju Ferry Port and its relationship with the socio-technical system components, we refer to the Decree of the Minister of Transportation of the Republic of Indonesia No. KM 2 of 2022 concerning the determination of shipping lanes, route systems, traffic procedures, and ship berthing areas of Mamuju Port (Ministry of Transportation, 2022a). This document covers the arrangement and organization of inbound and outbound passenger/vehicle operational flows, both from the seaside and from the land side. These operational flows are then linked to data on the technical and social components that directly contribute to supporting these operations. Figure 55 shows the results of the data synthesis that led to the concept of the Mamuju Ferry Port as a socio-technical system, illustrated with a block diagram. The block diagram in Figure 55 is divided into three main blocks, namely the operational, technological, and social subsystem blocks. In the operations block, port operations are categorized into two groups based on the area of operation. These two categories are quay and berth operations. A more detailed explanation of each operation is given below.

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[22] The social components included in this table are only those directly related to field operations. This data excludes other departments, such as branch managers, HR officers, and finance officers.

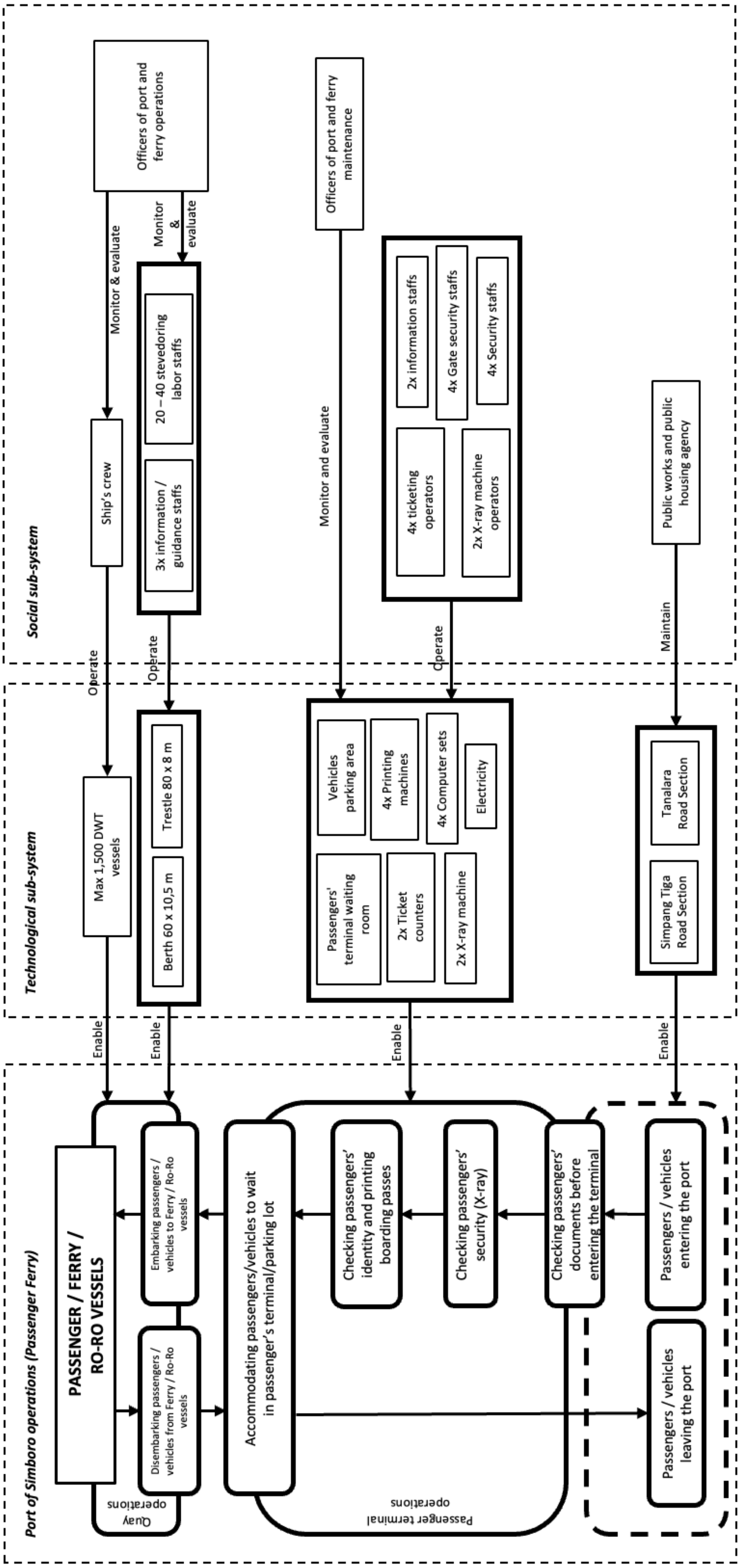

Figure 55. The conceptualization of Port of Mamuju Simboro and its operations as a socio-technical system

Firstly, the quay operations serve the arrival and departure of passenger vessels in the form of ro-ro vessels at Mamuju Simboro Port. The passenger vessels served by this port are generally 1,500 DWT. Ro-Ro vessels owned by state-owned companies (such as PT. ASDP Indonesia) or private shipping companies load and unload passengers in this port section. In addition to passengers, motorized vehicles and trucks are also loaded and unloaded at this location. An example of vessels operating in 2021 and owned by PT ASDP Indonesia is the Laskar Pelangi Passenger Motorboat (KMP) on the Mamuju - Balikpapan route. The other vessels are privately owned. Quay operations are supported by a 60 x 10.5-meter berth for vessels to dock. Between the berth and the passenger terminal is an 80 x 8-meter trestle, which is used for queuing passengers and vehicles to board the vessel. Three staff members are in charge of directing passengers to the ship and carrying out the final checks. In addition, 20 loading and unloading staff or porters are available to help passengers carry goods to and from passenger ships. Port and ferry operations officers supervise and evaluate all operations in the quay operations section.

The second area of operations at Mamuju Simboro Port is passenger terminal operations. In the passenger terminal operation, passengers who wish to board the ship are directed to the port terminal for security screening, check-in, and boarding pass printing. Early passengers will be directed to wait in the passenger terminal waiting room. Vehicles using the ferry will be directed to the car park area following the same procedure. Once the vessel has arrived, passengers and vehicles will be directed to the berth where the vessel is moored. This passenger terminal can also be used to wait for passengers who have just arrived at Mamuju Simboro Port.

The technical components to support the operation of the passenger terminal consist of 2 x-ray machines for security screening, four sets of computers and printers for printing passenger boarding passes, and a waiting area for passengers and vehicles wishing to cross. During the busy season, terminal operations are supported by 4 gate security officers responsible for security checks at the terminal gate, two x-ray machine operators responsible for checking passengers' luggage before entering the terminal, four ticketing officers, and two staff responsible for providing information on ship departure and arrival schedules. The Port and Ferry Maintenance Officer from PT ASDP Indonesia supervises and evaluates the operations in this section.

The two operations mentioned above are the primary operations at Mamuju Ferry Port. To reach Mamuju Port, passengers and vehicles can use two roads, Simpang Tiga road and Tanalara road. In 2021, the condition of the access roads to and from the Mamuju ferry port was quite good. Both road sections are approximately 6 meters wide with asphalt or flexible pavement.

6.1.2 Analysis of Sulawesi Island’s Ferry Ports-Hinterland Network Connectivity

In this subsection, we analyze the condition of the ferry port-hinterland connectivity network on Sulawesi Island. The analysis conducted in this subsection focuses on the connectivity between the ferry ports and the road network on Sulawesi Island. To analyze the Ferry Ports-Hinterland network connectivity, the main information needed is the alternative ferry ports available on Sulawesi Island, along with how much capacity is available and how much is used daily. The amount of capacity and average daily usage only considers passenger capacity. This consideration is made because individuals are the largest consumers of inter-island ferry services.

Based on data from the Central Bureau of Statistics (2022a), 20 passenger ferry ports are operating on the island of Sulawesi. This list of ports is then adjusted based on the port's location. The main criterion is whether it can be used as an alternative port in the event of disruptions to the Mamuju port, and whether it can be reached by land. Another criterion for selection is that the port must serve a ferry route that is also served by the port of Mamuju, connecting the island of Sulawesi with the province of East Kalimantan. Based on these criteria, three ports were selected that met the criteria. The ports meeting these criteria are located on the western side of Sulawesi Island, spread over three provinces: Central Sulawesi, West Sulawesi, and South Sulawesi. Table 50 shows the list of alternative ferry ports selected to replace the function of Mamuju Port if it is disrupted. Data on theoretical port capacity per day and average daily port usage are based on data from the Ministry of Transportation (2020). The next step is to calculate the value of the SC_p and $SCRI_p$ metrics, as explained in Chapter 3, to calculate how much capacity each alternative ferry port can make available as spare capacity if Mamuju Ferry Port cannot operate.

Table 50. List of alternatie ferry ports on Sulawesi Island and their capacity in 2020

Alternative ferry ports on Sulawesi Island	Theoretical port capacity per day (Passengers)	Average daily port usage (Passengers)
Pantoloan	493	189
Taipa	161	96
Pare-pare	374	148

Table 51 shows alternative ferry ports on Sulawesi Island and their Spare Capacity (SC_p) and Percentage of Demand Served by Replacement Port ($SCRI_p$) values. SC_p represents the passenger capacity available at these alternative ports that could potentially replace Mamuju Port in case of a disruption. $SCRI_p$, on the other hand, expresses the percentage to which these alternative ports could meet the demand from Mamuju Ferry Port if it were to become inoperable (178 passengers per day). The SC_p calculations are based on passenger units (persons) to emphasize the role of these alternative ports in replacing the passenger demand of Mamuju Ferry Port in case of a disruption. The results indicate that ports with sufficient capacity to fully accommodate (100% or more) the passenger demand from Mamuju Port are located in Central Sulawesi province, north of Mamuju, and in South Sulawesi. Notably, Pantoloan and Pare-Pare Port emerge as a prime candidate. It is crucial to acknowledge that no alternative ports within the same province (West Sulawesi) as Mamuju possess the necessary SC_p.

Table 51. The SC_p and $SCRI_p$ value of ports in Sulawesi to replace the lost capacity from the Port of Mamuju Simboro

Alternative ferry ports on Sulawesi Island	Daily Spare Capacity in Persons (SC_p)[23]	Daily Spare capacity replacement per port ($SCRI_p$)[24]
Pantoloan	304	171%
Pare-Pare	226	125%
Taipa	65	43%

The following analysis focuses on road connectivity, modeled as edges of the ports-hinterland network in Sulawesi Island. This analysis aims to measure how accessible Mamuju Ferry Port is from the alternative ferry ports on Sulawesi Island. This accessibility is expressed through the $N_p(t)$[25] metric with the calculation formula described in Equation (4). In this case study, the calculation of $N_p(t)$ uses a fleet of passenger buses with 32 seats, commonly used as the mode of land transportation connecting ports. This type of bus can carry a maximum of 20 kg of luggage from each passenger. Figure 56 shows an illustration of a typical bus as a land transportation mode that connects ports in Sulawesi Island.

Figure 56. Photo illustration of land transportation connecting passenger ports on Sulawesi Island (Courtesy of Perum DAMRI operational branch Mamuju, 2022)

To calculate the value of dt_p, data on various road sections connecting the alternative ferry ports with Mamuju Simboro ferry port is required. The value of dt_p is the value taken from the shortest round-trip time among all available road options. If there is more than one road route connecting Mamuju Port with other alternative ports, then the value of dt_p taken is the lowest travel time value of these routes. To analyze this, data from the Indonesia Spatial

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[23] The SC_p value is determined by calculating the difference between the port's maximum capacity and the average daily number of passengers using the port.

[24] The $SCRI_p$ value is determined by calculating the ratio of available spare capacity at the alternative port to the daily passenger demand at Mamuju Simboro Port (~178 passengers per day).

[25] $N_p(t)$ is "the number of inland transport resources required per day to utilize the spare capacity of alternative ports at the given period of t under normal conditions."

Data Catalogue (Ministry of Public Works and Housing, 2022) was used to identify which roads connect the alternative ports with the Mamuju ferry port.

The travel time required by a bus with a capacity of 32 passengers from Mamuju Port to other alternative ports was then calculated for each available road section. Table 52 shows the various alternative road options connecting Mamuju Port with alternative ferry ports. Figure 57 shows the spatial distribution of road networks connecting the Mamuju Ferry Port with other passenger ports in Sulawesi that serve the route to East Kalimantan Province. Other information included is the road segment name, terrain/road type, distance, and average one-way travel time in minutes for a bus, along with the specifications previously mentioned. Note that the one-way trip calculation also considers rest time if the distance traveled is long.

Table 52. List of roads connecting the Port of Mamuju to other alternative passenger ports on Sulawesi Island

Origin - Destination	Name	Terrain / Type	Distance (km)	Average one-way Travel Time (Min)*
Pantoloan - Mamuju	Palu – Mamuju Main Road	Coastal flat road	359	550
Taipa - Mamuju	Palu – Mamuju Main Road	Coastal flat road	402	620
Pare-Pare – Mamuju	Mamuju – Majene Main Road	Coastal flat road	288	464

*) The value of the travel time of a 32-passenger inter-port connector bus.

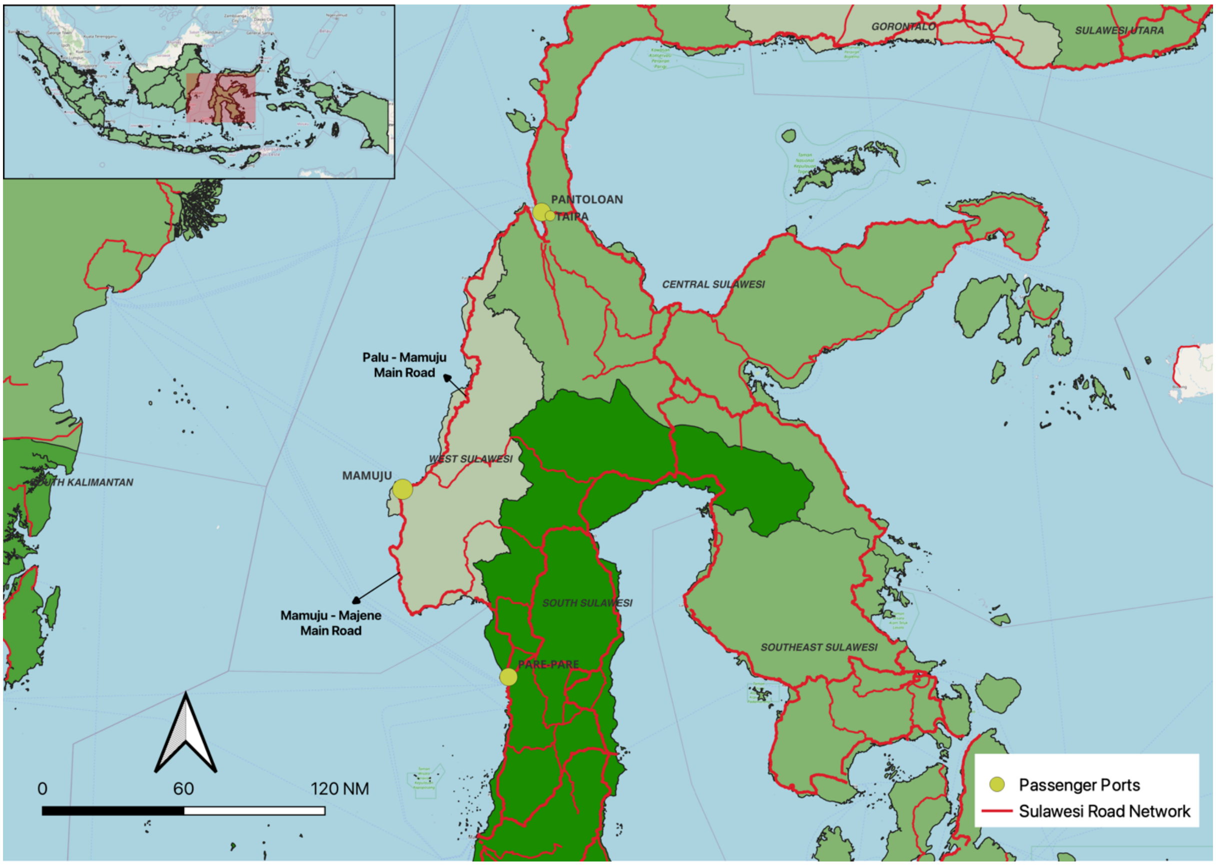


Figure 57. The spatial distribution of Ports-Hinterland Network connecting Mamuju Simboro Port with alternative passenger ports on Sulawesi Island

Now that the value of SC_p and the value of dt_p are found, the value of $N_p(t)$ can be calculated. $N_p(t)$ is the value of "*the number of inland transport resources required per day to utilize the spare capacity of alternative ports at the given period of t under normal conditions.*" This value shows how many resources are required to use the spare capacity available at alternative ports if Mamuju port operations are closed. The equation to calculate the $N_p(t)$ value can be found in Equation (2) in Chapter 3. Table 53 shows how many buses are required to capture the port spare capacity per day, or $N_p(t)$.

Table 53. Number of buses needed to capture the alternatie port spare capacity per day, $N_p(t)$

Port/airport	SC_p	$SCRI_p$	**Average round trip travel time in hours (dt_p)**	**Minimum number of buses needed to capture the port spare capacity per day $N_p(t)$**
Pantoloan	304	171%	18.33	5
Pare-Pare	226	125%	15.46	4
Taipa	65	43%	20.66	5

Based on the analysis results shown in Table 53, Mamuju Simboro Ferry Port has several alternative ports that can be used during a disruption. The first option is to use the spare capacity of Pare-Pare Port in South Sulawesi. Pare-Pare Port has enough spare capacity to cover 100% of the transport needs of Mamuju Port. In addition, due to the relatively short distance, Pare-Pare Port requires fewer land transport resources to mobilize passengers compared to using the spare capacity of the second alternative at Pantoloan Port. However, both can fully meet the needs of Mamuju Port. The other alternative is the port of Taipa, which is close to the port of Pantoloan. Assuming that both ports can handle the passenger flow from Mamuju Port, Taipa Port, and Pantoloan Port, both require a resource of 5 buses per day. However, Taipa Port is the least interesting alternative, considering that the spare capacity to cover the demand at Mamuju Port is only 43%.

6.1.3 Analysis of Sulawesi Island's Passenger Shipping Network Connectivity

In this section, we analyze the maritime connectivity for passengers on Sulawesi Island. This analysis aims to understand the spatial context of maritime connectivity for passengers on Sulawesi Island and the role of Mamuju Port relative to other ports. This section's analysis is limited to maritime transportation connectivity for passenger crossings connecting Sulawesi Island with Kalimantan Island. This restriction is made because Mamuju Simboro Port is a ferry port.

The connectivity of ferries from Sulawesi Island is then calculated based on the connectivity value of each port i on Sulawesi Island that has a maritime route with East Kalimantan province. The connectivity value of each port in this case study is based on the multiplication of the maximum theoretical capacity of ferry or ro-ro vessels that can carry passengers (in units of passengers) visiting port i by the frequency of ship visits in a given period. Using Equation 2, the connectivity level of passengers in Sulawesi with East Kalimantan Province is the sum of the total connectivity of all individual ferry ports in Sulawesi

Island that provide voyages to that province. In this case study, we only focus on analyzing passenger motor vessels, both ferries and Ro-Ro vessels.

Data for this connectivity analysis cannot be obtained from AIS and INAPORTNET because both systems do not record port calls at passenger ferry ports. Meanwhile, data from SIMLALA cannot be used because the record of ship operation plans in SIMLALA is only for cargo ships. To overcome this, we used internal data from PT ASDP Indonesia, a state-owned enterprise assigned by the government to operate ferry ports in Indonesia. The data from PT ASDP Indonesia records what passenger ships enter and exit the ferry port, which is taken from Ferrizy, an online ticketing platform for ferry services. The data from PT ASDP Indonesia includes commercial ships and ships subsidized by PT ASDP as a public service obligation. The data obtained includes ship name, port of origin, port of destination, day of departure, date of departure, and time of departure as shown in Table 54. To strengthen the analysis, we also interviewed several persons from PT ASDP Indonesia to validate the analysis and empirical findings.

Table 54. A number of example records of the dataset used in the analysis

No	Vessel Name	Port of Origin	Port of Destination	Day of Departure	Date of Departure	Time of Departure
1	KMP Laskar Pelangi	Kariangau	Mamuju	Tuesday	22-Aug-23	18.00 Local Time
2	KMP Laskar Pelangi	Mamuju	Kariangau	Wednesday	23-Aug-23	18.00 Local Time
3	KMP Laskar Pelangi	Kariangau	Mamuju	Thursday	24-Aug-23	18.00 Local Time
4	KMP Laskar Pelangi	Mamuju	Kariangau	Friday	25-Aug-23	18.00 Local Time

Based on the dataset from PT ASDP Indonesia, passenger connectivity between Sulawesi Island and East Kalimantan province was analyzed based on all passenger ships connecting routes between the two routes. The dataset we analyzed ranges from January 16, 2020, to January 16, 2021, or for one yearduring the COVID-19 pandemic. We assume that the data we get represents normal conditions (not affected by disasters) that describes the daily activities of the port during the COVID-19 pandemic. The calculation results of passenger connectivity between Sulawesi Island and East Kalimantan Province can be seen in Table 55.

Table 55. Passenger shipping connectivity to East Kalimantan from Sulawesi Island from January 16, 2020 to January 16, 2021

Rank	Port	Arrival (Debarkation)	Departure (Embarkation)	Total Connectivity	Average connectivity per day (in Passenger / Day)
1	Mamuju	26,700	21,928	48,628	133
2	Taipa	13,049	7,026	20,075	55
3	Pare - Pare	20,243	22,827	43,070	118
4	Pantoloan	18,045	19,550	37,595	103
Sulawesi Island’s connectivity to East Kalimantan Province		78,037	71,331	149,368	409

The empirical findings show that four main ports on Sulawesi Island directly connect to ferry ports in East Kalimantan Province: Mamuju Port, Taipa Port, Pare-Pare Port, and Pantoloan Port. Mamuju Port has the highest connectivity among these ports, accounting for approximately 33% of the total ship capacity, and facilitating the link between Sulawesi Island and East Kalimantan Province. East Kalimantan Province holds significant importance in Indonesia, as it is planned to become the Republic of Indonesia’s new administrative center and capital, replacing Jakarta. Based on the available data, it can be estimated that a disruption in Mamuju Port's operations would result in a loss of approximately 33% of Sulawesi Island's connectivity with East Kalimantan Province. Figure 58 illustrates the spatial distribution of passenger ferry ports on Sulawesi Island that maintain connectivity with East Kalimantan Province.

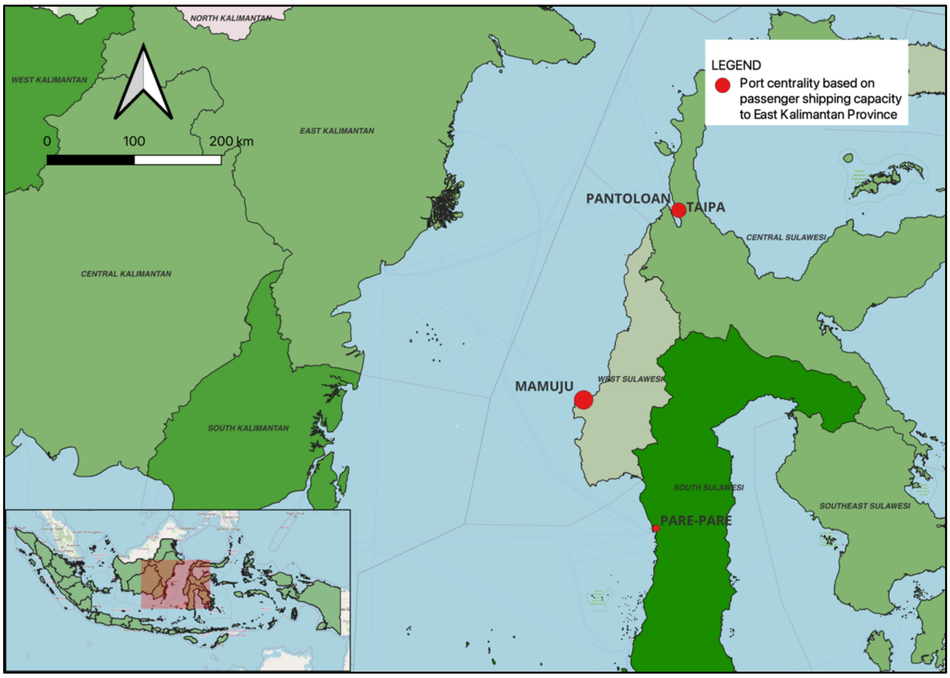


Figure 58. Spatial distribution and centrality (indicated with the size of the dot) of passenger ports based on the connectivity to East Kalimantan province

Following the analysis of Sulawesi Island's connectivity with East Kalimantan Province, we examine the connectivity of passenger shipping services specifically connected to Mamuju Port. Analyzing the connectivity of each route will serve as a baseline benchmark to determine whether there is a significant change in shipping connectivity at Mamuju Port when it was affected by a natural disaster. Data from Ferrizy is once again utilized to analyze the various passenger shipping services directly connected to East Kalimantan Province. Table 56 presents the origins and destinations of shipping services directly connected to Mamuju Simboro Port. The data spans the period from January 16, 2020, to January 16, 2021.

Table 56. List of passenger shipping services (inbound and outbound) that connected to the Port of Mamuju from January 16, 2020 to January 16, 2021

Inbound Edge (Debarcation)	**Passenger shipping connectivity**	**Outbound Edge (Embarcation)**	**Passenger shipping connectivity**
Penajam - Mamuju	10,720	Mamuju – Balikpapan	10,233
Samarinda – Mamuju	8,934	Mamuju – Parepare	7,308
Majene – Mamuju	7,147	Mamuju – Samarinda	5,895
Balikpapan - Mamuju	8,933	Mamuju – Penajam	5,800
Total	35,734		29,236

Figure 59 depicts the spatial distribution of passenger shipping services directed towards the Port of Mamuju, represented by inbound edges. The size of each vertex represents the overall connectivity level of that port compared to other ports in the region. In other words, this connectivity level considers both direct connections to the Port of Mamuju and indirect connections through other ports. The thickness of the edges represents the capacity of each shipping service for each pair of ports. Based on the data gathered, Mamuju Port serves ferry services from four ports: Penajam Port, Samarinda Port, Majene Port, and Balikpapan Port. Connectivity with Penajam Port accounts for the most significant proportion. This is attributed to the increasing ferry traffic resulting from the relocation of Indonesia's capital from Jakarta to Nusantara in Penajam Paser Utara, East Kalimantan. Meanwhile, ferry traffic from Samarinda and Balikpapan is relatively similar. Majene Port, having the lowest proportion, facilitates short-sea shipping among cities on Sulawesi Island.

Figure 60 illustrates the spatial distribution of passenger shipping services operating on outbound edges from the Port of Mamuju towards other ports in East Kalimantan Province. Four main ferry ports are connected to the Port of Mamuju. Ferry vessels from the Port of Mamuju serve routes to the Port of Balikpapan, Samarinda, and Penajam in East Kalimantan Province, accounting for 75% of the total outbound ferry services from Mamuju Port. Unlike inbound edges, voyages to the Port of Balikpapan dominate outbound services from the Port of Mamuju to outside of Sulawesi Island. This is due to the frequent movement of people for trade, work, and family visits from Mamuju to Balikpapan. Additionally, direct routes from Mamuju Port to Penajam Port are less common, and most voyages still utilize a route that transits Balikpapan Port before heading to Penajam Port. Moreover, Pare-Pare Port in South Sulawesi Province is served by a short-sea-shipping service connecting cities within Sulawesi Island, accounting for around 15%.

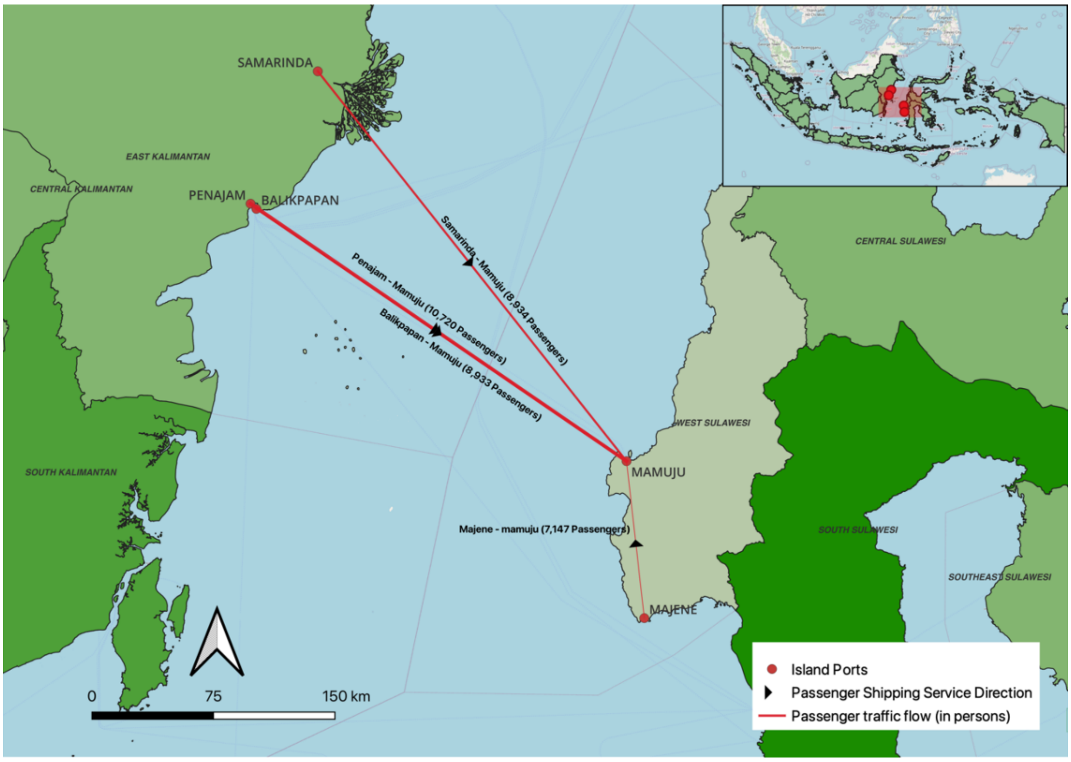


Figure 59. Inbound passenger flow to Mamuju Simboro Port during normal times (2020 - 2021)

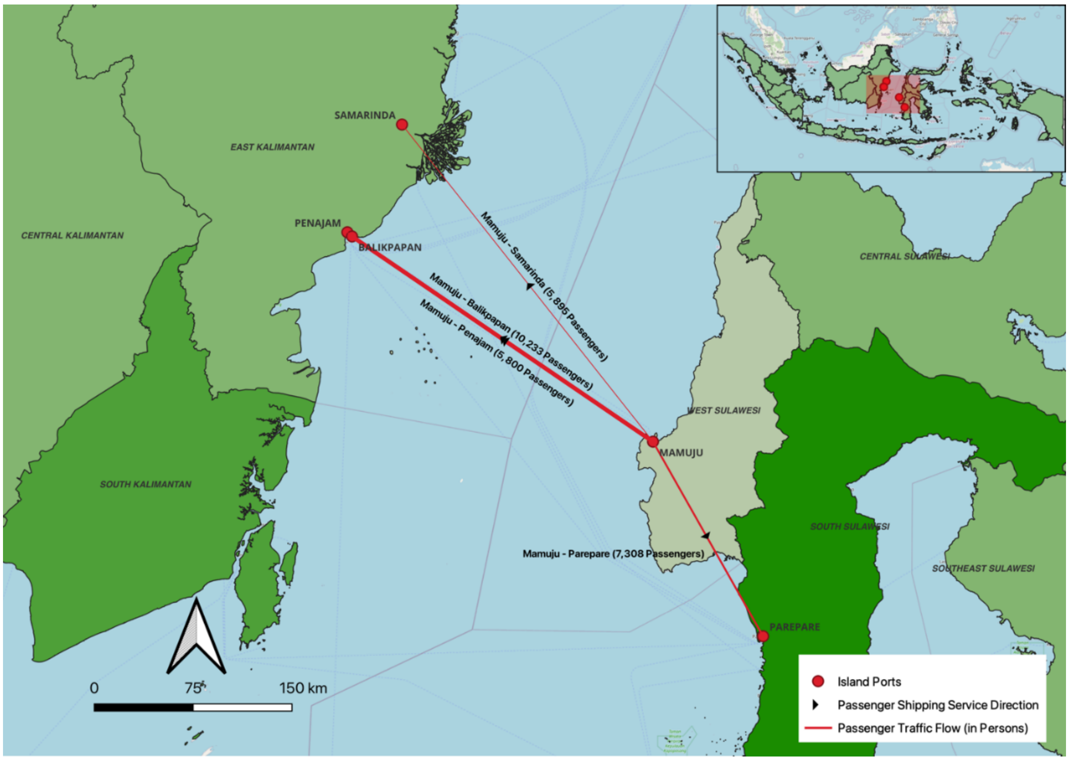


Figure 60. Outbound passenger flow to Mamuju Port during normal times (2020 - 2021)

6.2 Phase 2: Resilience Curve Analysis

This section covers the implementation process and outcomes of Phase 2 of the empirical resilience evaluation method proposed in this study, termed resilience curve analysis. It will illustrate how the Mamuju earthquake impacted the operational performance of Mamuju Port over time using the resilience curve methodology conceptualized in Chapter 2. Before conducting a resilience curve analysis, primary indicators for measuring the performance of the Port of Mamuju before and after the disaster must be established. In this case study, the chosen primary performance indicator is related to the port's ability to serve the needs of the Sulawesi Island community in embarking or disembarking passengers.

The primary indicator for constructing the resilience curve is passenger vessel capacity (PVC). PVC is a metric we propose to assess the capacity of passenger embarkation and disembarkation services at Mamuju Port within a specific timeframe. The unit of measurement for PVC is the number of passengers. The formula for calculating PVC involves summing the maximum theoretical capacity of all vessels visiting Mamuju Port during the specified period. An example of PVC calculation is as follows. Suppose the Port of Mamuju serves two ferry vessels during two days, each with a maximum capacity of 300 and 400 passengers. The PVC value at Mamuju Port during that period would be 700 passengers. This 700-passenger value reflects Mamuju Port's performance in handling ferry services for passenger embarkation or disembarkation. The experts have also validated using PVC as the primary indicator for effectively representing the service performance of non-commercial ferry ports in Indonesia.

Data from Ferrizy was utilized to develop the resilience curve for this case study. Based on Ferrizy's data, we could identify ticket sales and ferry vessel arrival and departure schedules to Mamuju Port. The Ferrizy data spans two years, from September 2020 to December 2022.

This timeframe was chosen to examine Mamuju Port's performance dynamics, encompassing the periods before, during, and after the Majene earthquake in January 2021. The ferry service schedule data from Ferrizy was then cross-checked with relevant stakeholders at Mamuju Port, and plotted in a graph for the empirical resilience curve for Mamuju Port, see Figure 61.

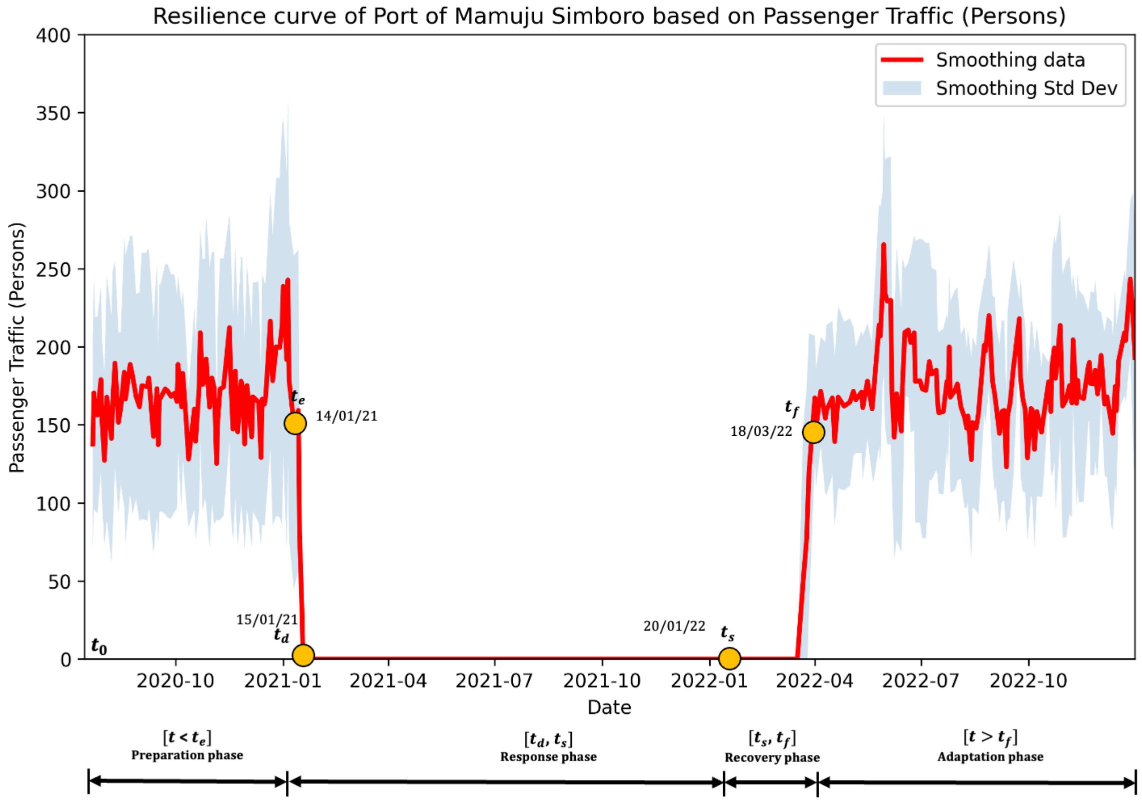


Figure 61. The empirical resilience curve of Port of Mamuju presented in a 3-day moving average

Based on the empirical resilience curve constructed in Figure 61, we identified four change points on the graph indicating significant changes in the over-time performance behavior of Mamuju Port. Each change point represents one or more events that significantly altered the trajectory of port performance behavior. Identifying these change points is crucial for determining the periods of the phases within the resilience cycle, such as the preparation, response, recovery, and adaptation phases. A detailed description of the four change points is presented in Table 57.

Table 57. Key changepoints detailed in the empirical resilience of the Port of Mamuju Simboro

Point symbol	Date point	Events
t_e	January 14, 2021	An earthquake with a magnitude of 5.9 M struck the Mamuju region in West Sulawesi at 2:35 PM (local time)
t_d	January 15, 2021	An aftershock with a magnitude of 6.2 M struck the Majene region in the early morning hours at 2:28 AM (local time). PT ASDP Indonesia Ferry (Persero) temporarily suspended operations at Mamuju Port, West Sulawesi, due to the early morning earthquake.
t_s	January 20, 2022	The Head of the West Sulawesi Transportation Agency announced that Mamuju Ferry Port has been repaired and will be operational in February 2022.
t_f	March 18, 2022	The inaugural voyage to Mamuju Port (from Balikpapan) marked the resumption of the Balikpapan-Mamuju route after Mamuju Port was rendered inoperable due to the January 15, 2021 earthquake. The berthing vessel was the Laskar Pelangi Ferry from Balikpapan, East Kalimantan, carrying 138 passengers.

Based on the changepoints identified above, we can determine the periods of each phase of the resilience cycle. Identifying these phases can be useful for identifying resilience attributes based on time duration. Furthermore, identifying the phase periods can also be useful for identifying the strategies stakeholders take to enhance resilience and their impact on resilience. Four phases have been identified: the preparation phase, the response phase, the recovery phase, and the adaptation phase.

Preparation phase: This phase represents the period when the port's performance was normal and is calculated as the period before the earthquake disaster, specifically before January 14, 2021, or it can be written symbolically as $t < t_e$.

Response phase: This phase started on January 15, 2021 (changepoint t_d), when PT ASDP Indonesia Ferry responded by closing the port due to the earthquake. The response phase ends at the changepoint t_s when the Mamuju Port is fully repaired. The duration of the response phase is approximately 370 days.

Recovery phase: This phase starts at changepoint t_s and ends at changepoint t_f, where ship visits to Mamuju Port returned to normal. The duration of the recovery phase is approximately 57 days.

Adaptation phase: This phase represents the period after the port's performance has returned to its original state, symbolized by $t > t_f$.

After identifying the changepoints and phases in the resilience cycle, we can calculate various attributes for Mamuju Port for the Majene Earthquake. These attributes can be categorized into those measured based on changes in port performance values and those measured based on phase durations in the resilience cycle. The theoretical formulas used for the calculations are presented in Chapter 2, which discusses the theoretical foundation of this research. The calculation results for each resilience attribute, along with the theoretical formulas and justifications, are shown in Table 58.

Table 58. The empirical resilience attributes of the Port of Mamuju, along with its reasoning based on the resilience curve

Resilience attributes	Theoretical formula	Empirical value	Reasoning
Robustness	Residual performance, $f(t_d)$	0 Passengers (per day)	$f(t_d)$ represents the residual performance of Mamuju Port at the time of its most severe impact due to the Majene earthquake, which occurred at changepoint (t_d). One day after the earthquake disaster (January 15, 2021), PT ASDP Indonesia Ferry decided to completely close the port due to the damage caused by the earthquake to several key infrastructure facilities at Mamuju Port.
Vulnerability	Depth of performance decline, $f(t_0) - f(t_d)$	178 Passengers (per day)	Empirical analysis revealed an average daily passenger ferry capacity of 178 at the Port of Mamuju. However, this capacity immediately dropped to zero following the earthquake due to the complete closure of port operations. The level of port vulnerability was calculated based on the experienced performance loss by subtracting the performance during the earthquake impact from the normal performance, resulting in a vulnerability level equivalent to 178 passengers.
Responsiveness	Duration of time spent at response phase $[t_d - t_s]$	370 Days	Responsiveness is measured by calculating the duration from the first announcement of the earthquake response (January 15, 2021) to the completion of repairs to critical port infrastructure and the resumption of port operations (January 20, 2022). The total duration between these two points is 370 days.
Rapidity	Duration of time spent in the recovery phase $(t_s - t_f)$	57 Days	Rapidity is measured by calculating the duration from the time the port's capacity is fully restored and ready for operation (t_s) until the port's performance returns to its pre-earthquake level (t_f). The total duration between these two points is approximately 57 days.
Recoverability	Speed of recovery, $\frac{df(t_{s2})}{dt}$	3 Passengers / day	Recoverability is determined by dividing the port's restored performance by the time taken to restore that capacity. Thus, the value can be calculated as 178 passengers/57 days = 3 passengers per day.

This subsection demonstrates the implementation of Phase 2, resilience curve analysis, for Mamuju Port, which was affected by the Majene Earthquake on January 15, 2021. The primary indicator used to construct the resilience curve in this case study is the port's capacity to handle passenger vessels, quantified using the Passenger Vessel Capacity (PVC) metric.

The empirical resilience curve has several benefits. First, it can serve as a reference for model development or to illustrate how Mamuju Port or similar ports would perform when affected by earthquakes with characteristics similar to the Majene Earthquake on January 15, 2021. Second, it can identify change points that significantly alter the behavior of port performance. Third, it can aid in deeper empirical analysis, such as determining resilience cycle phases, which can be used to calculate resilience attributes.

Resilience attributes are components that contribute to the overall resilience of a port. Attributes such as *robustness* or *vulnerability* can determine the ability of Mamuju Port to withstand earthquake damage. To calculate these two resilience attributes, two points are required: (1) The point representing the average port performance under normal conditions and (2) the point representing the port's performance when most severely impacted by the disaster.

Based on the analysis, the *robustness* value of Mamuju Port is 0 passengers, and the vulnerability level was 178 passengers. This is because PT. ASDP Indonesia Ferry, the port operator, decided to close the port entirely after the earthquake disaster. This policy prevented ferry ships from entering and exiting the port, resulting in a residual performance of 0 passengers. The vulnerability level indicates the performance loss experienced by the port due to the disaster. From the average performance value under normal conditions (around 178 passengers) to the value of 0, the vulnerability value was 178 passengers.

The *responsiveness* attribute measures the agility of stakeholders at Mamuju Port in preparing and managing resources to repair the operational capacity affected by the disaster. Two points are required to determine responsiveness: (1) The point in time representing the stakeholders' initial response (t_d); and (2) the point in time representing the completion of infrastructure repairs and the readiness for reoperation (t_s). The period between t_d and t_s is called the response phase in the resilience cycle, and this duration is used to measure port responsiveness. Based on the empirical data collected and analyzed, the responsiveness value of Mamuju Port was 370 days. This level of responsiveness over 370 days demonstrates the efforts of stakeholders and port actors to restore operational capacity and facilities to their pre-earthquake condition.

The point at which port performance has returned to its original condition (t_f) is crucial for calculating the resilience attributes *rapidity* and *recoverability.* These attributes measure how quickly the port's performance was able to return to a pre-disaster condition after all affected infrastructure was repaired and ready for reoperation (t_s). Rapidity represents the time from restoring port capacity (point t_s) to returning port performance to pre-disaster conditions (point t_f). Based on this, the empirical Port Rapidity value for Mamuju Port was 57 days. This indicates that, while the port's capacity had been restored, its performance did not immediately improve. There was a time delay before the port's capacity could be fully utilized again. Recoverability indicates the speed of recovery for Mamuju Port. Suppose it took 57 days to restore port performance after infrastructure repairs, with f(t_s) changing from 0 to 178 passengers (f(t_f)). In that case, the recoverability value of Mamuju Port was three passengers/day.

6.3 Phase 3: Disaster Impact Analysis

This section describes the third phase of the empirical analysis of port resilience methods: Disaster Impact Analysis. Phase 3 aims to explore the impact of the Majene Earthquake on Mamuju Port and the spatial network of the western part of Sulawesi Island, which provides passenger connectivity with East Kalimantan Province. This includes examining changes in the port-hinterland network connecting Mamuju Port to alternative passenger ports linking to East

Kalimantan Province and changes in shipping connectivity between Mamuju Port and other ports in East Kalimantan Province.

The analysis in this phase is divided into three subsections. Subsection 6.3.1 analyzes the impact of the Majene Earthquake on the socio-technical components of Mamuju Port. It is crucial to understand the factors behind the point t_d on the resilience curve and why the port robustness of Mamuju Port is only 0 passenger per day. Subsection 6.3.2 discusses how the Majene Earthquake impacted the ports-hinterland network of passenger ports in Sulawesi that connect to East Kalimantan Province. Subsection 6.3.3 examines the impact of the Majene Earthquake on the shipping connectivity of Mamuju Port with other ports in East Kalimantan Province.

6.3.1 Disaster Impact Analysis on the Port of Mamuju's Socio-Technical Components

This subsection analyzes how the Majene Earthquake on January 15, 2021, impacted the socio-technical components of Mamuju Port, leading to PT. ASDP Indonesia Ferry's decision to temporarily close the port's operations. Specifically, this subsection explains the state of the socio-technical components at the point on the resilience curve shown in Figure 61. We used data collected from mass media sources to analyze the earthquake's impact on these port components. A total of 29 media articles reported the impact of the Majene Earthquake on the socio-technical components of Mamuju Simboro Port (for more details, see the list of documents [6-1] to [6-29] at the end of this chapter).

To map and summarize the severity of the Majene Earthquake's impact on Mamuju Port, we employed the PIDA Sheet developed for this study. Figure 55 was revisited as a reference for the socio-technical components analyzed in this subsection. The analysis of the technical components of Mamuju Port included the berth (measuring 60 x 10.5 m), the trestle (measuring 80 x 8 m), the passenger terminal, the vehicle parking area, electrical installations, and administrative and security equipment such as ticket counters, printing machines, computer sets, and X-ray machines.

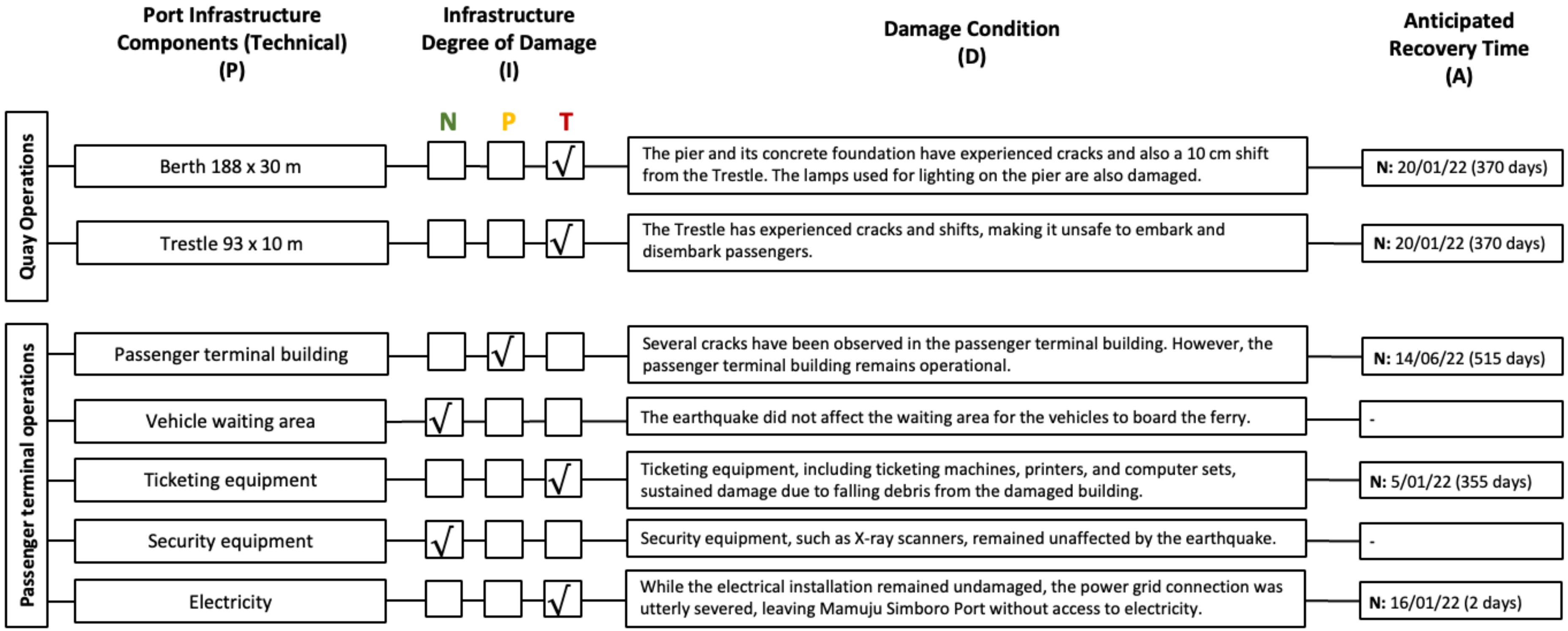
Figure 62 presents the empirical analysis results using the PIDA sheet for the technical components of the Mamuju Port affected by the Majene Earthquake. Based on the empirical analysis and the collected data, the most significant impact on the technical components of Mamuju Port was on the seaward side, namely the trestle and berth for ferry or Ro-Ro vessels. The primary earthquake impact on the berth was the cracking of the concrete foundation and a 10 cm shift from the trestle (Figure 64a). This increased the risk of accidents if the pier continued to be used for berthing ships. Meanwhile, another technical component, the trestle, experienced cracks along its length, making it unsafe for passenger loading and unloading. Figure 64b shows a warning sign for passengers to avoid the bridge and trestle area for safety. The damage to land-based components was not as severe as that on the seaward side. The terminal building suffered several cracks, and debris from the collapsed structure fell on ticketing equipment, rendering it unusable. Other affected technical aspects on land included the disruption of the electrical grid, leaving Mamuju Port without a power supply at that time.

Figure 63 visually represents the earthquake's social impact on Mamuju Port. This analysis shows the social aspects of the earthquake and their subsequent implications for port operations. Data gathered from the media indicates that the Majene earthquake did not cause fatalities among port employees. However, based on information obtained from the Head of UPP Class III Mamuju at the time, port employees could only work partially due to the impact of the disaster on many of the port employees' housing units (Figure 65 and Figure 66). The availability of employees at Mamuju Port remained partial until January 2022 due to the relocation of some port employees to a work unit at ASDP Balikpapan to handle the passenger traffic crossings in the area. The COVID-19 pandemic that peaked in Indonesia from April to September 2021 also hampered the repair of Mamuju Port and resulted in the continued deployment of employees to assist with port operations at ASDP Balikpapan. The return of Mamuju Port employees in January 2022 marked the return of the availability of port human resources, which took more than a year to achieve.

The findings are further visualized in a block diagram following the comprehensive analysis of the disaster's impact on social and technical components using the PIDA framework. Figure 67 presents a block diagram depicting Mamuju Port's social and technical components at point t_d. At point t_d, all operational processes at Mamuju Port, including quay and passenger terminal operations, were severely disrupted, leading to the temporary closure of the port. The empirical analysis revealed that technical factors were the primary cause of the port closure. The following is a description of the level of damage to the technical component:

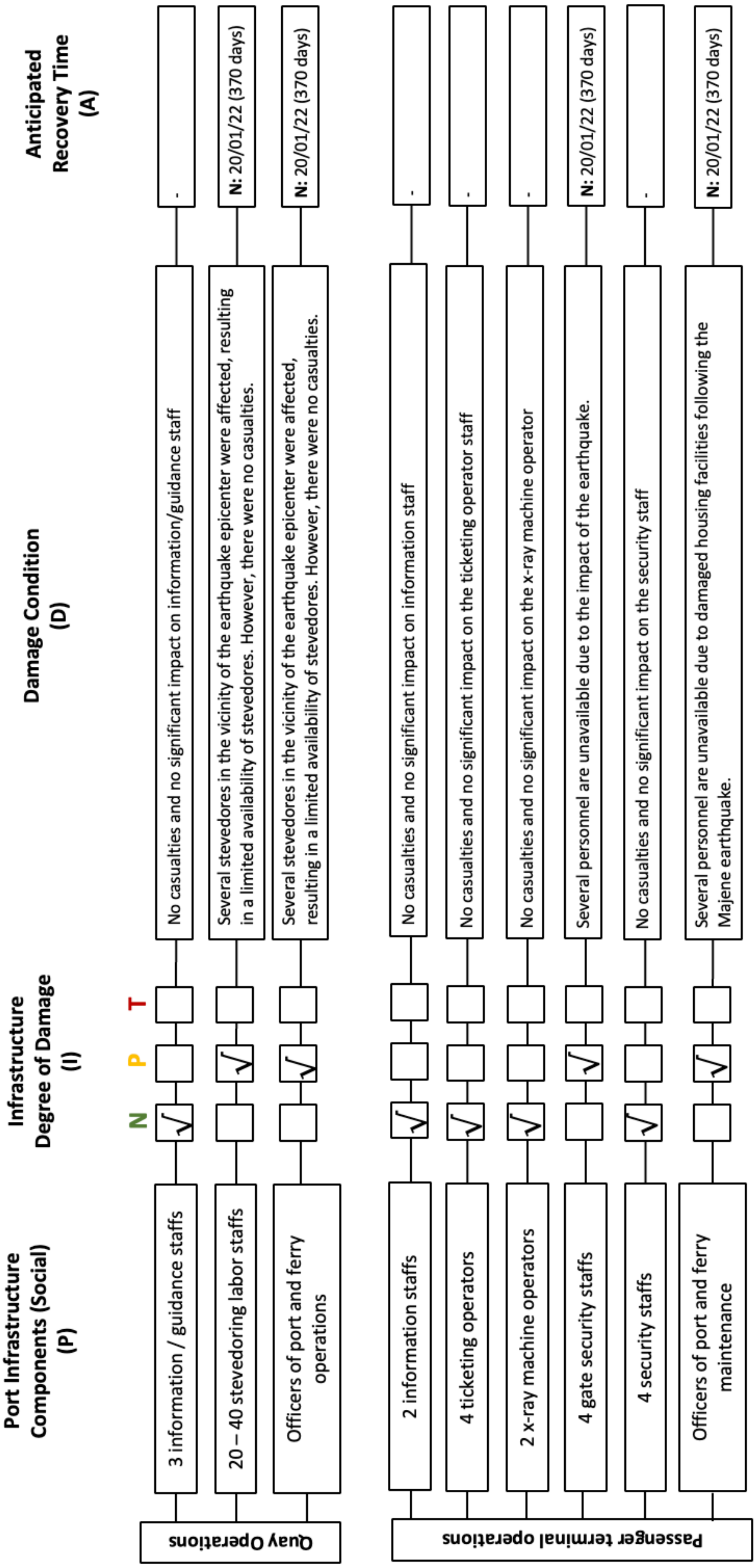
- **Quay Operations**: The extensive damage to berths and trestles rendered the port unsafe for embarking or disembarking inter-island ferry passengers.
- **Passenger Terminal Operations**: The malfunction of ticketing equipment and the complete loss of electricity supply to Mamuju Port rendered passenger terminal operations inoperable.

While the social impact was less severe, the earthquake affected several port staff and baggage handling workers, particularly those residing near the epicenter. This disruption was swiftly addressed by deploying unaffected personnel from available shifts.



	Port Infrastructure Components (Technical) (P)	Infrastructure Degree of Damage (I): N	P	T	Damage Condition (D)	Anticipated Recovery Time (A)
Quay Operations	Berth 188 x 30 m	☐	☐	√	The pier and its concrete foundation have experienced cracks and also a 10 cm shift from the Trestle. The lamps used for lighting on the pier are also damaged.	**N:** 20/01/22 (370 days)
	Trestle 93 x 10 m	☐	☐	√	The Trestle has experienced cracks and shifts, making it unsafe to embark and disembark passengers.	**N:** 20/01/22 (370 days)
Passenger terminal operations	Passenger terminal building	☐	√	☐	Several cracks have been observed in the passenger terminal building. However, the passenger terminal building remains operational.	**N:** 14/06/22 (515 days)
	Vehicle waiting area	√	☐	☐	The earthquake did not affect the waiting area for the vehicles to board the ferry.	-
	Ticketing equipment	☐	☐	√	Ticketing equipment, including ticketing machines, printers, and computer sets, sustained damage due to falling debris from the damaged building.	**N:** 5/01/22 (355 days)
	Security equipment	√	☐	☐	Security equipment, such as X-ray scanners, remained unaffected by the earthquake.	-
	Electricity	☐	☐	√	While the electrical installation remained undamaged, the power grid connection was utterly severed, leaving Mamuju Simboro Port without access to electricity.	**N:** 16/01/22 (2 days)

Figure 62. PIDA results from the technical component of the Mamuju Simboro Port. For Infrastructure Degree of Damage, N = Not affected, P = Partially affected, T = Totally unusable



	Port Infrastructure Components (Social) (P)	N	P	T	Damage Condition (D)	Anticipated Recovery Time (A)
Quay Operations	3 information / guidance staffs	√			No casualties and no significant impact on information/guidance staff	-
	20 – 40 stevedoring labor staffs		√		Several stevedores in the vicinity of the earthquake epicenter were affected, resulting in a limited availability of stevedores. However, there were no casualties.	**N:** 20/01/22 (370 days)
	Officers of port and ferry operations		√		Several stevedores in the vicinity of the earthquake epicenter were affected, resulting in a limited availability of stevedores. However, there were no casualties.	**N:** 20/01/22 (370 days)
Passenger terminal operations	2 information staffs	√			No casualties and no significant impact on information staff	-
	4 ticketing operators	√			No casualties and no significant impact on the ticketing operator staff	-
	2 x-ray machine operators	√			No casualties and no significant impact on the x-ray machine operator	-
	4 gate security staffs		√		Several personnel are unavailable due to the impact of the earthquake.	**N:** 20/01/22 (370 days)
	4 security staffs	√			No casualties and no significant impact on the security staff	-
	Officers of port and ferry maintenance		√		Several personnel are unavailable due to damaged housing facilities following the Majene earthquake.	**N:** 20/01/22 (370 days)

Figure 63. PIDA results from the social component of the Mamuju Simboro Port. For Infrastructure Degree of Damage, N = Not affected, P = Partially affected, T = Totally unavailable

Figure 64. 10 cm displacement of the trestle and berth connection (a); Warning sign for passengers to avoid the berth area due to damaged trestle of bridge structure (b)

Figure 65. The condition of residential houses around Mamuju Simboro Port was affected by the earthquake, and some of the residents are employees of the port.

Figure 66. The condition of several officer housing units at the Port of Mamuju Simboro following the Majene aftershock on the early morning of January 15, 2021.

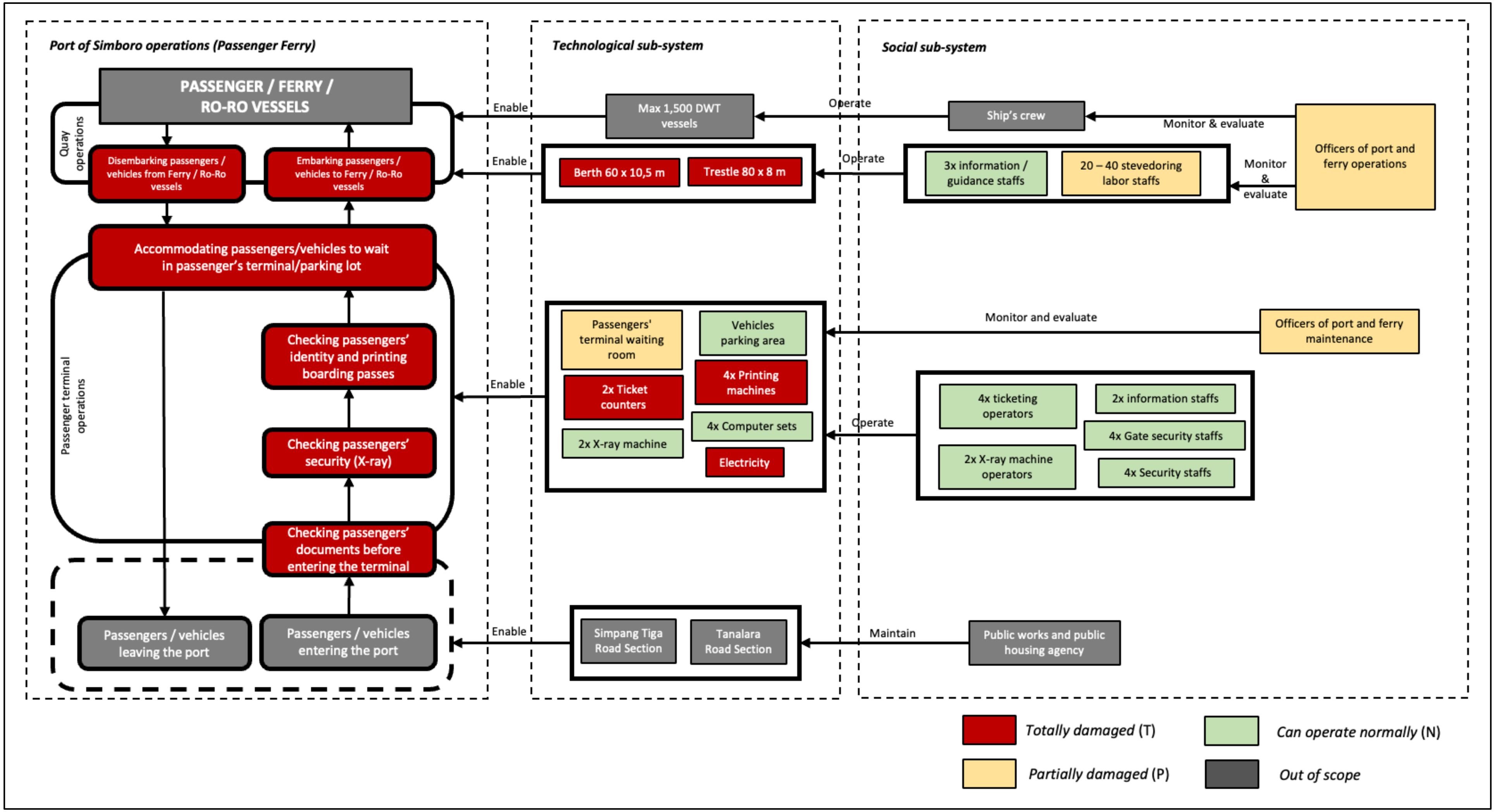


Figure 67. Block diagram derived from PIDA analysis result of sociotechnical components in the Port of Mamuju Simboro

6.3.2 Disaster Impact of the Sulawesi Island's Passenger Ports[26]-Hinterland Network Connectivity

This subsection shows the empirical analysis of the earthquake's impact on the connectivity of the ports-hinterland network, specifically focusing on passenger ports with ferry services between Sulawesi Island and East Kalimantan Province. The analysis is structured into two parts. The first part is Vertex Component Analysis. This part examines the impact of the Majene earthquake on the spare capacity of alternative passenger ports on Sulawesi Island that connect to East Kalimantan Province, excluding Mamuju Port. The primary metric to quantify these changes is the Spare Capacity Replacement Index for port p at the time t_d or ($\mathrm{SCRI}_p(t_d)$). The changes in SCRI_p values indicate that the earthquake also affected alternative ferry ports connecting Sulawesi Island and East Kalimantan Province.

Calculating the changes in SCRI_p values posed a significant challenge due to the unavailability of publicly accessible data from official sources. This limitation hindered our ability to directly quantify the earthquake's impact on the spare capacity of alternative passenger ports. To address this data gap, we adopted an alternative data collection approach, utilizing media reports as a valuable source of information. We meticulously selected media articles that focused on the situation near the alternative ports. These articles provided insights into the alternative ports' operational status and capacity constraints following the earthquake. A total of 19 media articles were carefully analyzed to extract relevant information (For more details, please refer to the list of documents [6-30] to [6-48] at the end of this chapter). The findings from this analysis are summarized in Table 59. This table presents the SCRI_p values for each alternative port before and after the earthquake, allowing for a quantitative assessment of the impact.

Our empirical investigation reveals that the Majene Earthquake primarily exhibited a single-vertex impact on the ports connecting Sulawesi Island and East Kalimantan Province. This implies that the earthquake's direct impact was concentrated only at the Mamuju Port, significantly affecting their shipping service capacity. The earthquake's impact on alternative ports stemmed from the surge in passenger demand following the disaster. Pantoloan Port is a compelling example of the earthquake's indirect impact on alternative ports. Despite not being directly affected by the earthquake, the Port of Pantoloan experienced a decrease in its SCRI_p to ($\mathrm{SCRI}_p(t_d)$)value. This decline can be attributed to the temporary repurposing of the port as a distribution hub for humanitarian aid destined for Majene earthquake victims. The influx of large aid vessels overwhelmed the port's capacity, reducing its space for ferry operations.

The analysis in the second part of this subsection focuses on the edges of the road network that connect the Port of Mamuju with other alternative crossing ports that provide crossing services to East Kalimantan Province. The main objective of this second stage analysis is to determine whether there was a change in the road network's capacity. The main metric to measure the road capacity is the number of buses (DAMRI Buses with a capacity of 32 seats) needed to utilize the port's spare capacity per day after the disaster or $N_p(t_d)$.

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[26] The passenger ports discussed in this subsection are limited to the island's passenger ports on Sulawesi Island which are connected to East Kalimantan Province.

Table 59. Changes in spare capacity at passenger alternative ports in Sulawesi Island following the Majene Earthquake

Alternative ports in Sabu Island	**Daily Spare Capacity at the time t_d in passenger ($SC_p(t_d)$)**	**Spare Capacity Replacement Index per Port at time t_d ($SCRI_p(t_d)$)**	**%change**	**Remarks**
Taipa	77	43%	0%	The shaking from the Majene earthquake was not felt in Central Sulawesi, and therefore did not have an impact on the sociotechnical aspects of the port. The port was operating as usual following the Majene earthquake disaster.
Pare-Pare	223	125%	0%	The shaking from the Majene earthquake was felt as far as Pare-Pare in South Sulawesi, but there was no damage to physical infrastructure or loss of life.
Pantoloan	125	70%	-101%	The shaking from the Majene earthquake was not felt in Central Sulawesi. The changes in values at Pantoloan Port are due to the use of some of the port's capacity as a hub for humanitarian aid for the victims of the Majene earthquake.

To calculate the value of $N_p(t_d)$, the average one-way travel time for each road section using buses with a passenger capacity of 32 at t_d, or $dt_p(t_d)$, is required. To calculate the value of $dt_p(t_d)$, data is obtained from articles in the mass media. To calculate the value of $dt_p(t_d)$, secondary data obtained from documents containing various incidents on the road sections traveled by buses is investigated (please refer to documents [6-32] to [6-37] at the end of this chapter.). Table 60 lists all the road sections that were physically affected by the Majene Earthquake and how this affects the value of $dt_p(t_d)$. This road data is from publicly accessible data, such as Google Maps.

Table 60. The impact of the Majene Earthquake on the ports-hinterland network in Sulawesi Island

Origin - Destination	Road segment name	Terrain / Type	Distance (km)	Average one-way Travel Time at time t_d (Min), $dt_p(t_d)$	Condition
Pantoloan – Mamuju	Jl. Poros Majene – Mamuju dan Jl. Poros Palu – Mamuju (Route 1)	Coastal flat road	411	700 (+45 minutes)	The main road from Majene to Mamuju in the direction of Palu was closed due to a minor landslide.
Pare – Pare Mamuju	Jl. Poros Majene – Mamuju (Route 2)	Coastal flat road	288	950 (+ 500 minutes) / Impassable for 3 days	The main road from Majene to Mamuju in the direction of Makassar was closed due to a severe landslide.
Taipa - Mamuju	Jl. Poros Majene – Mamuju dan Jl. Poros Palu – Mamuju (Route 1)	Coastal flat road	402	680 (+45 minutes)	The main road from Majene to Mamuju in the direction of Palu was closed due to a minor landslide.

Based on the analysis results presented in Table 60, we found that the earthquake affected all road sections connecting Mamuju Port with alternative passenger ports on Sulawesi Island that have routes to East Kalimantan Province. The most severe impact was on the Poros Majene-Mamuju road section, which heads to the south of Sulawesi Island. This road section was closed due to landslides in several parts of the road, which caused total traffic congestion. According to information from the mass media, the travel time could take 500 minutes longer, compared to normal conditions. Meanwhile, the Poros Majene-Mamuju road section heading to Palu experienced a slight impact, with some roads being closed but not severely. This caused the travel time from Mamuju Port to other alternative ports heading to North Sulawesi Island to increase by around 45 minutes.

Figure 68. A road section on route 2 was completely blocked by landslides, making it impassable for vehicles (a); A road section on route 1 that was affected by landslides but remains passable for vehicles (b) (Courtesy of detik.com)

Having assessed the direct impacts of the Majene earthquake on the Sulawesi road network connecting Mamuju Port with alternative passenger ports having connectivity to East Kalimantan Province, the value of the required bus resources, $N_p(t_d)$, to transport passengers to alternative ports during Mamuju Port's operational disruption can be calculated. The value of $N_p(t_d)$ indicates the level of connectivity between alternative passenger ports with connectivity to ports in East Kalimantan Province. This connectivity level is determined by considering the daily available spare capacity values at each alternative port at time t_d, represented by the symbol ($SC_p(t_d)$), and the average round-trip travel time at time t_d, obtained by multiplying the one-way travel time by two, or $2{*}dt_p(t_d)$. Using Equation 2 from Chapter 3, the calculation results of $N_p(t_d)$ can be seen in Table 61.

Table 61. Number of trucks required to transport passengers from the Port of Mamuju Simboro to the alternative ports that connect East Kalimantan Province to Sulawesi Island

Alternative ferry ports on Sulawesi Island connected to East Kalimantan Province	Daily Spare Capacity in Persons at time t_d ($SC_p(t_d)$)	Average round trip travel time in hours at time t_d ($2{*}dt_p(t_d)$)[27]	Number of buses needed to capture the port spare capacity per day at time t_d ($N_p(t_d)$)
Pantoloan	530	23	16
Taipa	150	22	4
Pare-Pare	425	32	18

Based on the impact of the Majene Earthquake on port-hinterland network connectivity in Sulawesi Island, we found that Mamuju Port had two alternatives to divert traffic to. The first alternative was to use the alternative ports to the north of Mamuju Port, namely Pantoloan Port and Taipa Port. These two ports could provide spare capacity up to 113% of the total needs of Mamuju Port when it was completely disrupted. Road access to the ferry ports in the northern region was not affected much by the earthquake. However, the vertex impact was larger for Pantoloan Port, which had to reduce its spare capacity due to its conversion into a hub for humanitarian aid. The second alternative to divert traffic was using the alternative port south of Mamuju Port, namely Pare-Pare Port in South Sulawesi. This port could provide a reserve capacity of 125% of the total capacity requirement of Mamuju Port. The biggest challenge for the ports in the south was the road access that was completely blocked due to the Majene earthquake, causing major congestion. However, when comparing the two, using the capacity at the Southbound ports was still better because it could cover the entire capacity needs of the disrupted Mamuju Port.

6.3.3 Disaster Impact Analysis on Sulawesi Island's Passenger Shipping Network Connectivity to East Kalimantan Province

In this subsection, we analyze the changes in passenger shipping network connectivity in East Kalimantan province due to operational disruptions at Mamuju Port. No public AIS data is available to analyze these changes due to the port's relatively small size and the smaller size of the ships served. Additionally, data such as SIMLALA only records permits for cargo ship routes and does not indicate whether ships adapt routes during operational disruptions at Mamuju Port. To overcome this, we scrapped data from a publicly accessible website, Roro

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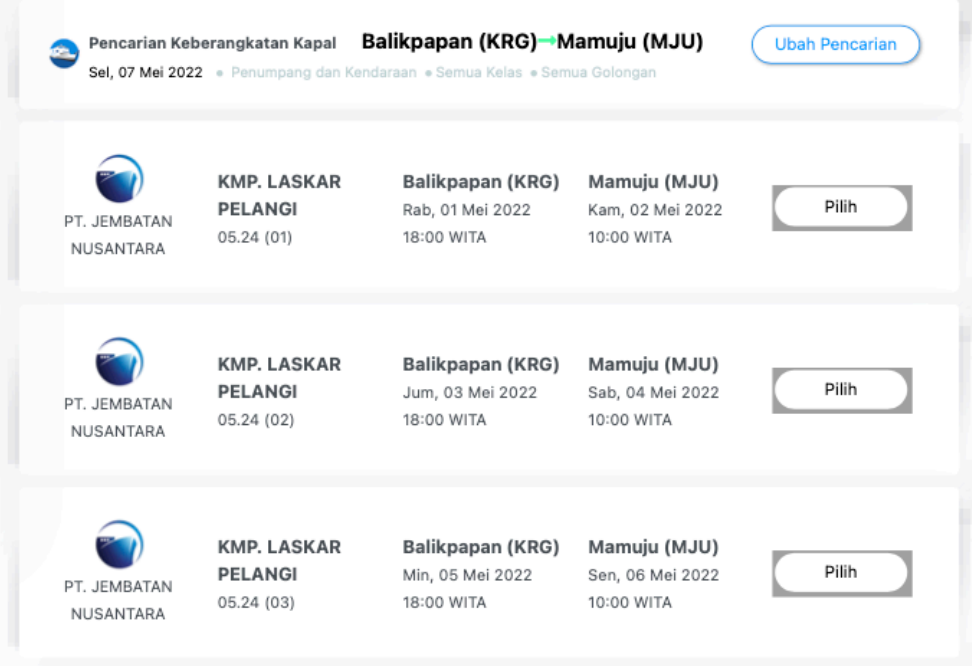
[27] The justification for the value of average round trip travel time in hours can be seen in Table 60

Prahu Hub. The data on this website shows what services are available throughout the year. We extracted route pair data as shown in Table 56, for the periods of the response phase $[t_d, t_s]$ and also the recovery phase $[t_s, t_f]$. The appearance of the data portal we used to perform this disaster impact analysis is shown in Figure 69.


Pencarian Keberangkatan Kapal Balikpapan (KRG) → Mamuju (MJU)

Sel, 07 Mei 2022 • Penumpang dan Kendaraan • Semua Kelas • Semua Golongan

PT. JEMBATAN NUSANTARA	KMP. LASKAR PELANGI 05.24 (01)	Balikpapan (KRG) Rab, 01 Mei 2022 18:00 WITA	Mamuju (MJU) Kam, 02 Mei 2022 10:00 WITA
PT. JEMBATAN NUSANTARA	KMP. LASKAR PELANGI 05.24 (02)	Balikpapan (KRG) Jum, 03 Mei 2022 18:00 WITA	Mamuju (MJU) Sab, 04 Mei 2022 10:00 WITA
PT. JEMBATAN NUSANTARA	KMP. LASKAR PELANGI 05.24 (03)	Balikpapan (KRG) Min, 05 Mei 2022 18:00 WITA	Mamuju (MJU) Sen, 06 Mei 2022 10:00 WITA

Figure 69. Data display from the portal used to analyze changes in sea connectivity at Mamuju Port empirically

Similar to the previous subsection, the analysis in this section is conducted on both vertex and edge components. For vertex analysis, each port involved in the passenger shipping network connected to Mamuju Port will be examined for changes in connectivity following the Majene Earthquake. The changes in each pair of ports connected to the Mamuju Port will be examined for edge analysis. The analysis is divided into two timeframes. The first timeframe is the response phase $[t_d, t_s]$, as shown in the resilience curve in Figure 61. The second timeframe focuses on the recovery phase $[t_s, t_f]$. These two timeframes are chosen to understand how the passenger shipping connectivity conditions changed following the Majene Earthquake disaster. The data we obtained was processed based on its timeframe and then compared to normal conditions.

Analysis of the disaster impact on passenger shipping network connectivity between Sulawesi Island and East Kalimantan Province during the response phase $[t_d, t_s]$

Table 62 presents the changes in ferry port connectivity compared to normal conditions during the response phase $[t_d, t_s]$, while Table 63 presents the changes in ferry shipping service connectivity connected to Mamuju Port compared to normal conditions during the response phase $[t_d, t_s]$.

Table 62. The connectivity of passenger ports on Sulawesi Island with East Kalimantan Province during Response Phase [t_d, t_s] compared to the daily average of normal conditions before the Majene Earthquake

Rank	**Port**	**Port connectivity (in passenger) at [t_d, t_s], $C_{ij}[t_d, t_s]$**	**Average connectivity per day at [t_d, t_s] (in Passenger / Day)**	**Change of connectivity per day during [t_d, t_s] (%)**
1	Mamuju	0	0	-178 (-100%)
2	Taipa	19,936	96	+41 (+75%)
3	Pare-Pare	54,112	249	+101 (+68%)
4	Pantoloan	56,010	189	+36 (23%)
Sulawesi Island's connectivity to East Kalimantan		195,028	534	0 (0%)

Despite the complete closure of Mamuju Port, Table 62 indicates that connectivity between Sulawesi Island and East Kalimantan Province remained relatively unchanged. This is evident from the comparable connectivity levels observed during normal and post-Majene earthquake conditions. This resilience was attributed to the adequate reserve capacity of alternative ports, which effectively compensated for the lost capacity of Mamuju Port. For instance, Pantoloan and Taipa Ports, located north of Mamuju Port, also served as alternative ports for ferry services to East Kalimantan Province. Apart from those ports, Pare-Pare Port, situated south of Mamuju Port, emerged as the primary alternative destination to divert traffic from Mamuju Port. This preference stemmed from two factors:

1. ***Shorter travel time from Mamuju Port***. Initially, landslides blocked access roads to Pare-Pare Port, rendering them impassable. However, this disruption was temporary, lasting only three days. By January 19, 2021, the Public Works and Housing Ministry (PUPR) had cleared the roads using heavy machinery. Consequently, from January 19, 2021, many passengers who previously relied on Mamuju Port to travel to East Kalimantan Province switched to Pare-Pare Port.
2. ***Increased bus fleet accessibility.*** In addition to the shorter travel time, the number of buses available to access Pare-Pare Port in South Sulawesi also increased. This led to an increase of passengers using Pare-Pare Port.

Complementing our vertex-based analysis that focuses on the empirical examination of ship connectivity changes at the port level, we also analyzed shipping service dynamics shifts, representing the edges of the passenger shipping network between Sulawesi Island and East Kalimantan Province. Our analysis is confined to the changes or reactions of shipping services on passenger ferries connected to Mamuju Port in response to the operational disruptions caused by the Majene Earthquake. The reactions we analyzed fall into four categories: rerouting, skipping, canceling, and no change.

The analysis is further restricted to the initial inbound trajectory to facilitate the examination of routes exclusively connected to Mamuju Port. Table 63 presents the analysis results of shipping service responses following the closure of Mamuju Port operations. Data was collected from the ASDP website during the response phase, encompassing vessel routes (tracks) for commercial and pioneer ferries.

Table 63. Analysis of shipping service responses following the closure of Mamuju Port during the response phase [t_d, t_s]

Initial inbound trajectory	Response link	% Estimation of diverted shipping capacity (based on nr of passengers)	Type of response
Penajam – Mamuju	Penajam - Balikpapan	100%	Rerouting
Balikpapan – Mamuju	Balikpapan - Pare - Pare	100%	Rerouting
Majene – Mamuju	Majene - Taipa	100%	Skipping
Samarinda - Mamuju	Samarinda - Pantoloan	26%	Rerouting
	Samarinda - Taipa	44%	Rerouting
	Samarinda - Banjarmasin	30%	Rerouting

Based on the analysis results in Table 63, several dynamic changes can be observed in passenger shipping services connected to Mamuju Port during the response phase. At this time, Mamuju Port operations were closed entirely, and the physical infrastructure affected by the Majene earthquake was being repaired. During this phase, it was found that shipping services from Penajam Port to Mamuju were suspended, and instead, they focused on connecting crossings between Penajam and Balikpapan.

Passengers from the Penajam and Balikpapan areas were consolidated from Balikpapan Port before crossing to Sulawesi Island through Pare-Pare Port. Ships from Penajam are generally government-subsidized pioneer ships with a final stop at Mamuju Port. For example, if these ships were to reroute to serve voyages to Pare-Pare Port directly, they would have very high operating costs. They would not be a government target, as their primary purpose is establishing connectivity with Mamuju Port. Meanwhile, ships from Samarinda reacted by rerouting to Taipa Port, Pantoloan Port, and Balikpapan Port. This varied rerouting is because ships from Samarinda Port are predominantly commercial, resulting in a more diverse rerouting pattern.

Analysis of disaster impact on passenger network connectivity in Sulawesi Island during the recovery phase [t_s, t_f]

This section will specifically examine the impact of the Majene Earthquake on the shipping network from Sulawesi Island connected to East Kalimantan Province for the recovery phase [t_d, t_s]. This analysis studies the shipping services in the aftermath of Mamuju Port's reopening and the gradual return to pre-disaster traffic levels. Table 64 charts the evolution of port connectivity during the recovery phase.

Table 64. The connectivity of Passenger Ports on Sulawesi Island with East Kalimantan Province during Recovery Phase $[t_s, t_f]$ compared to the daily average of normal conditions before the Majene Earthquake

Rank	**Port**	**Port connectivity (in passenger) at $[t_s, t_f]$, $C_{ij}[t_s, t_f]$**	**Average connectivity per day at $[t_d, t_s]$ (in Passenger / Day)**	**Change of connectivity per day during $[t_d, t_s]$ (%)**
1	Mamuju	0	0	-137 (-77%)
2	Taipa	19,936	96	+0 (+0%)
3	Pare-Pare	54,112	249	+41 (+68%)
4	Pantoloan	56,010	189	+0 (0%)
Sulawesi Island's connectivity to East Kalimantan		195,028	534	0 (0%)

Table 64 shows a modest increase in traffic at Mamuju Port, indicating its gradual recovery following the earthquake-induced infrastructure damage. The observed traffic surge at Mamuju Port can be attributed to the traffic diversion from Pantoloan Port and Taipa Port, both situated north of Mamuju Port. Most ships returning to Mamuju Port were public service vessels, which had legal provisions to sail on the route to Mamuju Port. Privately owned ships still had to re-apply for shipping route permits through SIMLALA in order to be able to serve requests at Mamuju Port again. In the recovery phase, Pare-Pare Port remained the primary alternative port, awaiting traffic to fully shift back to Mamuju Port. A more detailed analysis of shipping service passenger dynamics during the recovery phase is provided in Table 65.

Table 65. Edge analysis of the response from shipping services connected to Mamuju Simboro Port during the recovery phase

Initial inbound trajectory	**Response link**	**% Estimation of diverted shipping capacity (based on nr of passengers)**	**Type of response**
Penajam – Mamuju	Penajam - Balikpapan	0%	Unchanged
	Penajam - Mamuju	100%	Returning
Balikpapan – Mamuju	Balikpapan - Pare - Pare	41%	Rerouting
	Balikpapan - Mamuju	59%	Returning
Majene – Mamuju	Majene - Taipa	0%	-
	Majene – Mamuju	100%	Returning
Samarinda - Mamuju	Samarinda - Pantoloan	0%	-
	Samarinda - Taipa	0%	-
	Samarinda - Mamuju	100%	Returning

6.4 Phase 4: Resilience Intervention Analysis

This section analyzes the various interventions and the actors involved in enhancing Mamuju Port's resilience in the aftermath of the Majene earthquake. The resilience interventions examined encompass port-level (L1) and island transport-network-level (L2) measures. Thirty-eight mass media articles were analyzed to find the implemented interventions to increase Mamuju Port's resilience (please refer to articles [6-48] to [6-86] at the end of this chapter). The interventions were categorized based on the Resilience Curve periods outlined in Figure 61 to facilitate the intervention analysis. For this case study, the resilience intervention analysis is structured around the four distinct periods delineated in the Resilience Curve.

Beyond the phase-based analysis within the resilience cycle, additional information is incorporated to enhance the comprehensive understanding of resilience interventions:

1. ***Intervention Timeline***: The precise timing of each intervention is documented to provide a clear chronology of resilience-building efforts.
2. ***Decision-Making Actors***: The actors directly involved in the decision-making process for each intervention are identified, highlighting the roles and responsibilities of various stakeholders.
3. ***Theoretical Category***: Each resilience intervention is categorized according to relevant theoretical frameworks, enabling a deeper understanding of the underlying principles and approaches employed.
4. ***Intervention Level:*** The level of intervention is determined, distinguishing between port-level (L1) interventions focused on enhancing the resilience of Mamuju Port itself and island transport-network-level (L2) interventions aimed at strengthening the broader transportation infrastructure that impacts the port's operations.

In the following subsections, we will show the specific resilience interventions identified within each phase of the resilience cycle.

6.4.1 Resilience Intervention Analysis in the Preparation Phase ($t < t_e$)

This subsection analyzes the resilience interventions implemented during the preparation phase, corresponding to the period $t < t_e$ in the Resilience Curve. Our analysis reveals a lack of concrete evidence that Mamuju Port undertook specific preparatory measures to mitigate the impact of natural disasters, particularly earthquakes. This observation is strengthened by statements from various parties involved in post-earthquake assessments, including the then-coordinator of earthquake mitigation efforts and representatives of the Meteorology, Climatology, and Geophysics Agency (BMKG) in West Sulawesi. These assessments highlight that public infrastructure, including Mamuju Port, was not designed to withstand seismic events of magnitude V-VI MMI.

Further evidence supporting that earthquake-resistant design standards were not applied in Mamuju Port's construction can be found in the port's master plan. This publicly accessible document outlines three phases for the port's development: Short-Term Development (2017-2021), Medium-Term Development (2017-2026), and Long-Term Development (2017-2039). Remarkably, none of these development phases incorporate plans for earthquake-resistant construction capable of withstanding strong tremors. Instead, the development focus lies primarily on expanding the port's area and increasing its capacity to accommodate the anticipated growth in passenger traffic.

6.4.2 Resilience Intervention Analysis during Response Phase [t_d, t_s]

This subsection examines resilience interventions implemented during the response phase for the Majene earthquake. The analysis period for the response phase spans from January 15, 2021 (point t_d), when the sociotechnical components of Mamuju Port were severely affected by the earthquake, to January 20, 2022 (point t_s), when the sociotechnical components essential for seaward operations were restored and ready for reopening.

The response phase lasted a considerable period of approximately 370 days. This extended response duration can be attributed to several factors. The first factor was the decision by PT. ASDP Indonesia Mamuju Branch to temporarily suspend operations at Mamuju Port and redirect available human resources to ASDP ports in Balikpapan and other ASDP ports serving as humanitarian aid hubs. This decision was made to secure the necessary repair funding, requiring approval from the central government and the House of Representatives of the Republic of Indonesia, a process that could take months. To prevent resource wastage, PT. ASDP Indonesia Mamuju Branch attempted to allocate its resources to other ports. However, while the physical infrastructure of Mamuju Port was severely impacted, the restoration of the road network connecting to alternative ports, such as the Majene-Mamuju and Mamuju-Palu routes, was completed within three days. This road repair significantly helped passengers who typically used Mamuju Port, enabling them to access alternative ports for crossings to East Kalimantan Province.

The second factor was the peak of the COVID-19 pandemic in Indonesia, known as the Delta variant wave. The peak of the COVID-19 pandemic occurred between May and August 2021. This resulted in many vital stakeholders being affected by the pandemic, either falling ill or even passing away. Consequently, coordination efforts to expedite the repair of Mamuju Port were hindered due to organizational restructuring, requiring organizations to adapt to maintain optimal performance. Following the subsiding of the COVID-19 Delta variant pandemic, PT. ASDP Indonesia began accelerating the repair process of Mamuju Port. PT. ASDP initiated repairs in September 2021, starting with a request for repair funding from the central government. In October 2021, the bidding process to select a repair contractor was completed, and the restoration process commenced on November 5, 2021. This repair process was completed within approximately two months, on January 21, 2022, indicating that the actual repair duration was not very long.

Table 66 provides a detailed list and explanation of resilience interventions during the response phase. The following table provides a detailed breakdown of resilience interventions implemented during the response phase ($t_e - t_s$) to enhance Mamuju Port's resilience against the impact of the Majene earthquake. Each intervention is categorized based on the level of intervention (L1: port-level, L2: island transport-network-level) and is accompanied by a brief description and corresponding timeline.

Table 66. Resilience interventions at Port of Mamuju Simboro during the response phase [t_e, t_s]. For the intervention category. Repu = Repurposing, Reloc = Relocation, Repa = Reparation, Recon = Reconstruction, OF = Operational Flexibility, OA = Organizational Agility

No	**Resilience interventions and level category**	**Time taken $[t_e - t_s]$**	**Category**						**Actors involved**
			Infrastructure adaptation				**Process adaptation**		
			Repu	**Reloc**	**Repa**	**Recon**	**OF**	**OA**	
1	PT. ASDP Indonesia Mamuju Branch announces port closure due to safety concerns following earthquake damage to technical components (L1)	15-Jan-21					√		PT. ASDP Indonesia Mamuju Branch
2	Central government, through the Ministry of Transportation of the Republic of Indonesia, sends an expert team to assess the impact of the Majene earthquake on the socio-technical infrastructure of Mamuju Port (L1)	16-Jan-21						√	Ministry of Transportation of the Republic of Indonesia
3	Restoration of full access to the Palu-Mamuju main road connecting Mamuju Port to alternative passenger ports, Pantoloan Port and Taipa Port (L2).	17-Jan-21			√				Ministry of Public Works and Public Housing (PUPR) of the Republic of Indonesia
4	Restoration of full access to the Mamuju-Majene main road connecting Mamuju Port to alternative passenger ports, Majene Port and Pare-Pare Port in South Sulawesi (L2).	18-Jan-21					√		Ministry of Public Works and Public Housing (PUPR) of the Republic of Indonesia
5	Release of the Earthquake Survey Report for the M 6.2 Mamuju Majene Earthquake by the Meteorology, Climatology, and Geophysics Agency of the Republic of Indonesia, including damage assessment and repair recommendations for Mamuju Port infrastructure (L1).	17-Feb-21						√	Meteorology, Climatology, and Geophysics Agency (BMKG) of the Republic of Indonesia
6	PT. ASDP Indonesia Mamuju Branch responds to the West Sulawesi Provincial Government, citing coordination and repair delays due to the challenges posed by the COVID-19 Delta variant pandemic (L2).	21-Feb-21						√	PT. ASDP Indonesia Mamuju Branch
7	Vice Governor of West Sulawesi sends a formal letter urging PT. ASDP Indonesia Mamuju Branch, the port operator, to expedite the repair of the damaged Mamuju Port (L1).	12-Jun-21						√	West Sulawesi Provincial Government

Table 66 continued

No	**Resilience interventions and level category**	**Time taken $[t_e - t_s]$**	**Category**						**Actors involved**
			Infrastructure adaptation				**Process adaptation**		
			Repu	**Reloc**	**Repa**	**Recon**	**OF**	**OA**	
8	PT. ASDP Indonesia Mamuju Branch responds to the West Sulawesi Provincial Government, citing coordination and repair delays due to the challenges posed by the COVID-19 Delta variant pandemic (L2).	8-Aug-21						√	PT. ASDP Indonesia Mamuju Branch
9	PT. ASDP Indonesia Mamuju Branch announces that the priority for repairing Mamuju Port will be on seaward facilities and that a budget request has been submitted to the central government for approval (L1).	4-Sept-21						√	PT. ASDP Indonesia Mamuju Branch
10	PT. ASDP Indonesia Mamuju Branch announces the completion of the bidding process for Mamuju Port repairs and the imminent commencement of repair work (L1).	15-Oct-21						√	PT. ASDP Indonesia Mamuju Branch
11	PT. ASDP Indonesia Mamuju Branch initiates the restoration of seaward technical infrastructure as the top priority to enable the earliest possible reopening (L1).	5-Nov-21			√				PT. ASDP Indonesia Mamuju Branch
12	PT. ASDP Indonesia Mamuju Branch announces the completion of seaward infrastructure restoration and the reopening of Mamuju Port for operational use (L1).	21-Jan-22			√			√	PT. ASDP Indonesia Mamuju Branch

6.4.3 Resilience Intervention Analysis during Recovery Phase [t_s, t_f]

This subsection focuses on the analysis of resilience interventions implemented during the recovery phase of Mamuju Port. The recovery phase started on January 20, 2022, when the seaside infrastructure of Mamuju Port was fully repaired and ready for operation, and concluded on March 18, 2022, when port traffic returned to normal levels. The duration of the recovery phase was 57 days.

During this phase, four resilience interventions were implemented to restore traffic between Mamuju and East Kalimantan Province as quickly as possible. The first intervention involved inter-branch coordination within PT. ASDP Indonesia. An example was the coordination efforts between PT. ASDP Indonesia Mamuju Branch and PT. ASDP Indonesia Balikpapan Branch. The Mamuju Branch requested the Balikpapan Branch to conduct an on-site assessment of the condition of the Mamuju Port after the repair. The involvement of the Balikpapan Branch aimed to leverage its expertise in assisting the Mamuju Branch in preparing for the resumption of Mamuju-Balikpapan route operations to pre-earthquake levels. The Mamuju-Balikpapan route is a crucial link between Sulawesi Island and East Kalimantan Province.

The second resilience intervention involved conducting technical trials before resuming port operations. This aimed to fulfill the safety requirements stipulated by the Mamuju Port Authority. The technical trials, conducted between late January and early February, ensured the pier's structural integrity and adherence to all safety standards before reopening. By the end of February 2022, the port operator had completed and submitted the port feasibility test results to the port authority, paving the way for issuing Sailing Permits (*Surat Persetujuan Berlayar/*SPB) for vessels intending to dock at Mamuju Port.

The third intervention entailed disseminating information to private parties and Pioneer ship operators regarding the readiness of Mamuju Port to resume operations. Formal letters were sent to several private companies and Pioneer operators, informing them of the port's reopening. However, despite the notification, shipping routes could not be immediately diverted as shipping operators had already published scheduled sailings for passengers until the end of February 2022.

The fourth intervention was undertaken by PT. ASDP Indonesia Mamuju Branch, which gradually released updates on the port's status through media articles and social media platforms. This aimed to inform the public in both Sulawesi Island and East Kalimantan Province that Mamuju Port was open and that passenger ferry services between Mamuju and East Kalimantan, particularly Balikpapan, would resume operations soon, with an estimated timeframe of February 2022 (pending the availability of services from shipping operators to reroute their vessels).

6.4.4 Resilience Intervention Analysis during the Adaptation Phase ($t > t_f$)

This subsection covers the resilience interventions undertaken to enhance the resilience of Mamuju Port during the Adaptation Phase. The pre-earthquake traffic recovery began on March 18, 2022, and this analysis focuses on the period thereafter. Examining these resilience interventions provides valuable insights into Mamuju Port's strategies to improve its resilience against future similar disasters. The analysis covers the period to the end of the year, December

31, 2022. Two primary resilience interventions were identified within this timeframe, as detailed below.

While Mamuju Port reopened for passenger services on March 18, 2022, the only repaired physical infrastructure components were those supporting seaport operations, such as docks (berths) and trestles. Landside infrastructure components, such as the passenger terminal, needed repair as well. PT. ASDP Indonesia Mamuju Branch had prioritized restoring seaport components to enable immediate port operations and prepare facilities for ship berthing. However, this decision left many passengers without adequate waiting areas. Figure 70 illustrates the lack of proper passenger waiting areas. Port authorities even used some port officer office spaces as makeshift waiting areas. In response to these conditions, port management now prioritized the renovation of the passenger terminal and other landside facilities during the Adaptation Phase. This decision was particularly crucial given the approaching Eid al-Fitr holiday on May 2, 2022, which was expected to cause a significant surge in passenger ferry demand. Landside facility repairs commenced on March 21, 2022, and were completed on April 29, 2022.

Figure 70. Mamuju Simboro Port passengers await on the passenger terminal platform amidst ongoing landside facility rehabilitation (Courtesy of Tribun-Sulbar news agency)

A second intervention aimed at enhancing security and disaster response by establishing a dedicated security unit and outpost. This initiative aimed to enhance security and provide a rapid response team during periods of high passenger volume, particularly during religious holidays or in the event of natural disasters. In late May 2022, a collaborative effort between port management and security forces, including the police and military, led to the formation of a dedicated security unit and outpost at Mamuju Port. The effectiveness of this intervention was evident during the 5.8 magnitude earthquake that struck Mamuju on June 8, 2022. The quake temporarily suspended shipping operations, leaving Mamuju Port inaccessible. However, the newly established security unit proactively assessed the situation and confirmed the port's safety, allowing for a swift resumption of operations within just four days. The rapid restoration of port operations was attributed to several factors, including the security unit's swift assessment and reassurance of shipping operators and passengers. The presence of this dedicated security unit provided confidence in the port's safety, facilitating a swift return to normal operations.

While establishing the security unit represented a significant step towards enhancing resilience, our analysis revealed a limited focus on improving the socio-technical components of Mamuju Port's infrastructure against earthquakes. The primary focus of interventions remained on physical repairs and reconstruction without incorporating additional measures to enhance earthquake resistance. Establishing the security unit and outpost is innovative, though. This collaboration between port operators and security forces demonstrates a proactive effort to address potential security concerns and ensure rapid emergency response.

6.5 Lessons Learned from Empirical Findings

This section synthesizes the key learnings derived from the empirical analysis using the four-phase methodology proposed in this study. It categorizes these learnings based on three resilience attributes: performance-based resilience (port robustness/vulnerability), time-based resilience (responsiveness), and performance per time-based resilience (rapidity/recoverability). The discussion highlights key takeaways and recommendations for improving these resilience attributes in contexts similar to the case study presented here. The case study in this chapter focused on a passenger ferry port managed by PT. ASDP Indonesia, a state-owned enterprise in Indonesia. The Port of Mamuju Simboro is a small-scale port with limited publicly accessible data, making direct empirical analysis of resilience challenging.

This section highlights the key takeaways and recommendations derived from the empirical analysis of port resilience attributes for the Port of Mamuju Simboro following the Majene Earthquake. The discussion is structured into three subsections, addressing performance-based resilience (port robustness/vulnerability), time-based resilience (responsiveness), and performance per time-based resilience (rapidity/recoverability).

Subsection 6.5.1 highlights the crucial lessons learned and recommendations for enhancing performance-based resilience attributes, specifically port robustness, which encompasses the ability of the Port of Mamuju to maintain residual port performance following an earthquake impact. Subsection 6.5.2 focuses on the time-based resilience attributes, particularly port responsiveness, which reflects the Port of Mamuju's ability to restore its operational capacity and receive incoming vessels swiftly. Subsection 6.5.3 studies the time-based resilience attributes, specifically rapidity and recoverability, which assess the Port of Mamuju's ability to restore port performance to pre-earthquake levels quickly.

The insights and recommendations presented in this section aim to empower the Port of Mamuju Simboro and other ports with similar characteristics to enhance their resilience against future earthquakes. By implementing these measures, ports can effectively safeguard their infrastructure, maintain operational continuity, and minimize seismic events’ economic and social impacts.

6.5.1 Lessons Learned Related to Port Robustness/Vulnerability

The empirical analysis using the resilience curve revealed that the Port of Mamuju theoretically possesses a robustness value of 0 passengers and a vulnerability value of 178 passengers (per day). The robustness value indicates that immediately following the earthquake, the Port of

Mamuju could not maintain any residual performance. The vulnerability value represents the daily passenger traffic loss following the impact of the Majene earthquake on the Port of Mamuju Simboro. Based on the empirical findings and the proposed methodology, several key lessons learned and recommendations for enhancing resilience attributes emerged:

1. The primary cause of the Port of Mamuju's complete operational shutdown following the Majene earthquake was damage to its technical components. This highlights the crucial need for earthquake-resistant port designs in regions prone to seismic events.

2. The earthquake's impact on the Port of Mamuju's technical components extended beyond the sea side (docks and trestle) to the land side (passenger terminals and port offices). While both contributed to the zero-passenger robustness value, the port operator's decision to close operations was primarily due to damage to sea-side facilities, not land-side damage. For small ports in island regions with limited budgets and frequent seismic activity, this serves as an empirical reference to prioritize strengthening sea-side technical infrastructure first, followed by land-side reinforcement.

3. The Majene earthquake disrupted the port’s technical components and the road network accessing alternative ports. In this case, the Poros Majene-Palu road, the sole land access to the Taipa and Pantoloan ports, was partially blocked by landslides, allowing only single-lane traffic. The Poros Majene-Mamuju road, the only land link connecting the Port of Mamuju to Pare-Pare, was completely closed, rendering it impassable. This has two implications: firstly, access to alternative ports became unavailable, and secondly, emergency assistance from other ports to expedite repairs at the Port of Mamuju was hindered, delaying the restoration of its residual performance. This emphasizes the need to consider the port components and the hinterland's impact when assessing earthquake impacts. The analysis suggests that the population may become isolated even if an island has multiple alternative ports, but without alternative road access.

Based on the lessons learned, the following recommendations are proposed to enhance the port robustness or reduce port vulnerability of the Port of Mamuju (or ports with similar contexts) against future earthquakes:

1. Raise awareness of emerging risks in earthquake-prone regions like Sulawesi and advocate for a different design approach for earthquake-resistant ports, that is more earthquake-prone than conventional ones.

2. Develop guidelines for earthquake-resistant port structure construction to guide the development of more resilient ports. These guidelines can be incorporated into the Port Master Plan (RIP), guiding port development in the short (5 years), medium (10 years), and long (15 years) terms.

3. Establish alternative routes to access alternative ports and inland destinations to enhance connectivity between the port and the hinterland network. Currently, only one main road provides proper access to alternative ports. When earthquakes have a widespread impact on ports and road networks, limited road connectivity can isolate island populations.

6.5.2 Lessons Learned Related to Port Responsiveness

This subsection presents the critical lessons learned from the empirical analysis of the proposed methodology in this study. The focus is on time-based resilience attributes, specifically port responsiveness. The port responsiveness value, determined from the constructed resilience curve, is 370 days. This represents the total duration from the initial response actions taken by Mamuju Simboro Port Authority following the Majene earthquake to the complete restoration of Mamuju Simboro Port infrastructure and its readiness for full-scale operations. In the context of this case study, port responsiveness ends when the port's sea-side infrastructure (berths and trestle) is fully repaired and deemed capable of accommodating berthing vessels. The following are the empirical lessons learned regarding port responsiveness at Mamuju Port:

1. Complex bureaucratic structures can significantly hinder timely action, prolonging port responsiveness. This was evident in the case of Mamuju Port, where PT. ASDP Indonesia, the port operator, lacked the budgetary authority to initiate repairs following the earthquake damage. Such authorization required the central government’s intervention, as a substantial portion of Mamuju Port's infrastructure is centrally owned, not by the port operator. Consequently, the budgeting and tendering processes involved multiple layers of approvals, resulting in long delays. The intricate web of bureaucratic procedures can impede rapid decision-making and resource allocation, particularly in emergency situations like natural disasters. This highlights the need for streamlining bureaucratic processes and establishing clear lines of authority to ensure timely and effective responses.

2. The COVID-19 pandemic had profoundly impacted port operations, exacerbating the challenges of complex bureaucratic structures and extending port responsiveness timelines. This case study of Mamuju Port highlights the pandemic's role in creating an increasingly complex, dynamic, ambiguous, and volatile coordination environment. The pandemic introduced additional layers of complexity to an already intricate bureaucratic landscape. Communication channels became strained due to remote work arrangements and social distancing measures, hindering the flow of information and decision-making processes. Moreover, the dynamic nature of the pandemic and the ever-changing public health guidelines introduced an element of ambiguity and uncertainty, further complicating coordination efforts. The volatile nature of the pandemic also presented significant challenges. Sudden surges in cases and the emergence of new variants necessitated rapid adjustments to protocols and procedures, placing further strain on already stretched resources. This volatility made it difficult to establish long-term plans and maintain consistent operations.

3. The prolonged port responsiveness in the aftermath of the earthquake and tsunami was partially mitigated by the responsive action of the Public Works and Housing (PUPR) Ministry in clearing landslide-blocked roads. Within four days, these efforts restored public access to alternative ferry ports, enabling the resumption of essential services. This case study highlights the critical role of rapid hinterland infrastructure restoration in enhancing the resilience of Mamuju Port. When primary port infrastructure is rendered inoperable, alternative access routes become essential for maintaining the flow of goods and persons. The prompt restoration of these routes by the PUPR Ministry played a crucial role in mitigating the impact of the disaster and accelerating the recovery process.

Based on the empirical findings presented, the following recommendations are proposed to enhance the port responsiveness of the Port of Mamuju and similar ferry ports:

1. ***Invest in Earthquake-Resistant Technology.*** To mitigate the impacts of the Majene earthquake, invest in earthquake-resistant technology. This includes implementing structural enhancements, adopting seismic-resistant construction materials, and utilizing advanced monitoring and control systems to safeguard port infrastructure against seismic events.

2. ***Allocate Emergency Response Funds.*** Establish a dedicated contingency fund or allocate a portion of the budget for disaster response to enable a prompt and effective response to future earthquakes. This fund should cover immediate repair costs, emergency supplies, and logistics support to minimize disruptions and expedite recovery efforts.

3. ***Establish Regional Collaboration Strategies.*** Establish collaborative agreements with alternative ports on the same island to facilitate seamless cargo diversion and passenger rerouting in the event of a disaster. This collaboration should encompass joint contingency planning, communication protocols, and resource-sharing mechanisms to ensure a coordinated and efficient response.

4. ***Establish Strategic Regional Short-Sea Inter-Island Services.*** Implement strategic regional short-sea inter-island services to enhance connectivity and provide alternative transportation options in case of disruptions to primary port operations. For instance, these services can connect smaller ports in East Kalimantan Province to ensure continued cargo movement and passenger access.

6.5.3 Lessons Learned Related to Port Rapidity/Recoverability

This subsection provides the key lessons learned regarding resilience at the Port of Mamuju based on the empirical analysis of the proposed methodology. The empirical values for port rapidity and port recoverability were 57 days and 3 passengers per day, respectively. The following lessons learned are associated with the performance-based and time-based resilience attributes:

1. The port authority’s unexpected introduction of technical trials following infrastructure restoration completion delayed the issuance of opening permits for Mamuju Port, further prolonging the port recoverability. This incident highlights the critical need for coordinated infrastructure completion and port operations to ensure a seamless transition back to normal operations. This underscores the importance of establishing clear communication channels and coordination mechanisms between the entities responsible for infrastructure restoration, port operations, and regulatory approvals.

2. Public service obligation (PSO) vessels demonstrated greater adaptability than commercial vessels, contributing to faster port rapidity and recoverability. This is attributed to the pre-existing one-year sailing permits for PSO vessels. In contrast, commercial vessels require re-applying for route permits to serve the Port of Mamuju using SIMLALA, which also has a one-year validity.

3. Prioritizing the repair of sea-side infrastructure over land-side infrastructure can accelerate port rapidity and recoverability. The Port of Mamuju's experience demonstrates that prioritizing sea-side infrastructure repairs enabled the port to resume passenger ship traffic promptly. Land-side infrastructure, such as passenger waiting areas, can be more flexible as it does not directly impact navigation safety and security. Prioritizing sea-side repairs is particularly advantageous for ports with limited infrastructure repair budgets, as sea-side repairs generally offer fewer alternative repair options than land-side repairs.

Based on the empirical analysis using the proposed methodology to assess performance-based time-based resilience attributes (port rapidity and port recoverability) at the Port of Mamuju following the Majene Earthquake, the following recommendations are highlighted to improve port rapidity and recoverability, which can also be relevant for similar ports:

1. ***Establish an Integrated Port Disaster Response Team (PDRT)***. To effectively manage disaster response and recovery efforts at the Mamuju Port, an integrated Port Disaster Response Team (PDRT) should be established. This PDRT should consist of critical stakeholders from the Mamuju Port, including the Port Authority, Port Operator, and Infrastructure Repair Contractor Lead. The benefits of an integrated PDRT are expected to enhance coordination, facilitate timely and informed decision-making, streamline permit issuance to the port’s reopening, and agree on the procedure of trial operations. The following are the examples of PDRT responsibilities:
    a. ***Regular meetings***: The PDRT will conduct regular meetings to discuss progress, identify potential roadblocks, and adapt the recovery plan.
    b. ***Infrastructure prioritization***: The PDRT will collaborate to prioritize which infrastructure should be repaired first, determine the repair procedures, and streamline permit issuance before the port can be reopened.
    c. ***Trial operations:*** To expedite port reopening, trial operations may be conducted once essential port infrastructure has been repaired.

2. ***Extend the validity period of sailing permits for PSO vessels.*** Recognizing that small ferry ports have limited resources for infrastructure restoration, resulting in extended recovery times, central governments could consider implementing a multi-year permit system for PSO vessels serving vital routes that face high disaster risks in archipelagic countries. For instance, PSO vessels and sea toll vessels serving the Port of Mamuju could be granted sailing permits for 2 to 3 years. This would provide strong legal backing for PSO vessel operators to promptly return to the Port of Mamuju without requiring re-application for sailing permits, especially when port recovery takes longer than a year.

3. ***Implement a fast-track mechanism for commercial vessel route permit processing in emergency situations.*** Currently, every commercial vessel seeking to operate must submit a ship's voyage plan (RPK) to the central government through SIMLALA. RPK approval typically takes 3 months. To expedite route change applications for commercial vessels affected by disasters, the government could prioritize such applications, particularly those proposing alternative routes that prevent the isolation of remote islands in the archipelago.

4. ***Prioritize sea-side infrastructure repairs to expedite port recovery***. This recommendation aligns with empirical evidence that sea-side improvements can expedite port operational recovery. When ports have limited funds for repair efforts, and archipelagic ports need to reopen promptly to prevent regional isolation, sea-side infrastructure can be prioritized to enable port operations to resume.

5. ***Employ modular and flexible buildings for land-side infrastructure in ports with high earthquake risk.*** Modular construction offers the flexibility to create buildings of any scale and allows for adding or removing building components as needs change. By utilizing modular buildings, land-side restoration can be expedited while enhancing structures' earthquake resistance for future events.

6.6 Concluding Remarks and Summary

This chapter describes implementing the port resilience evaluation method at the Port of Mamuju, a passenger ferry port in Sulawesi, Indonesia. The Port of Mamuju was selected to test the method's effectiveness in evaluating the resilience of small-scale passenger ferry ports with limited publicly available data. After analyzing the empirical findings, lessons learned that can be applied to other ports were also presented. The method was tested for the Majene Earthquake on January 15, 2021, with a magnitude of 5.9 on the Richter scale.

Section 6.1 demonstrates the implementation of the method in phase one, which involved empirically analyzing the port system and its island connectivity. The data used as input to analyze the port system context was non-public data. The only publicly available data at the time of this analysis was the Port Master Plan (RIP) for the Port of Mamuju, which handles cargo ships, not its passenger terminal. To address this, we used data from the Central Statistics Agency and experts from PT. ASDP Indonesia that is not publicly available.

To analyze the Port of Mamuju as a Socio-Technical System, we classified the data we collected into technical and social data. This technical data is divided into infrastructure data, operational flow data, and maintenance data (if any). The social data we obtained was classified based on demographic data, including the number of port workers, the organizational structure, and their job descriptions. To create a conceptual model of the Port of Mamuju as a socio-technical system, we also consulted with several experts who understand the field conditions at the Port of Mamuju. The output of this phase is a list of existing technical components (Table 48) and social components (Table 49) that support Port of Mamuju operations, as well as a conceptualization of the Port of Mamuju as a socio-technical system shown in Figure 55.

Section 6.1 also explains the level of connectivity of Sulawesi Island, which is relevant to the function of the Port of Mamuju on the island. The first analysis concerns ports-hinterland network connectivity, which is how the level of connectivity of the Port of Mamuju and alternative ports with the hinterland on Sulawesi Island. To analyze this, we used data that is entirely open to the public, namely the Ministry of Transportation Data Portal, the Sea Transportation Traffic Management Information System (SIMLALA) Data Portal, Port and Ferry Facilities/Infrastructure Data from the Provincial Transportation Agency in Sulawesi Island, and copies of the Governor's Decree in Sulawesi Island in Determining Existing Roads on Sulawesi Island.

Our method of processing this data was first to register all ferry ports operating in Sulawesi Island from the Ministry of Transportation Data Portal, and then to filter any ferry ports that serve crossings between Sulawesi Island and East Kalimantan Province through the SIMLALA Data Portal. The East Kalimantan Province boundary was chosen because the main role of the Port of Mamuju is to connect Sulawesi Island with East Kalimantan Province. Based on this data, it was found that the connectivity of Sulawesi Island with East Kalimantan Province is 195,028 passengers in 2020 or 534 passengers per day supported by 4 ferry ports, one of which is the Port of Mamuju.

Unfortunately, the three alternative ports besides the Port of Mamuju are located in different provinces, making the Port of Mamuju quite vulnerable in case of a disaster. Alternative ports such as Pantoloan, Taipa, and Pare-Pare have reserve capacities of 171%, 125%, and 43%, respectively. Each of these alternative ports has only one main access road from the port of Mamuju that can be used by buses to access the reserve capacity if the Port of Mamuju experiences operational disruptions. On the sea side, the largest connectivity of the Port of Mamuju is with the Port of Panajam (inbound) and the Port of Balikpapan (outbound). Connectivity with the Port of Panajam is driven by the relocation of the capital city, so many people in Kalimantan work there. The connectivity with Balikpapan is based on trade relations and also passenger movements for which demand has been established for a long time.

Section 6.2 explains the application of the resilience evaluation method in phase two, which is resilience curve analysis. The resilience curve is a commonly used method to describe the level of port resilience. To create a resilience curve, we used a single performance indicator, namely: Passenger Vessel Capacity (PVC). PVC shows the maximum theoretical capacity of passenger ships visiting Mamuju Port within a specific time frame. The ideal data to use as input for this phase is public data from official data recording agencies, such as from INAPORTNET or accurate data such as AIS. However, the Mamuju Ferry Port does not have complete data for both. Therefore, in this case study, we used data from an online platform for buying and selling inter-island ferry tickets, such as Ferrizy.

We extracted this data to determine the availability of ferry schedules for Mamuju Port within the period from September 1, 2020, to December 31, 2022, or for 2 years and 3 months. The data was then processed into a line chart using a 3-days moving average, where one data point shows the average passenger counts of the ship visits for 3 days at Mamuju Port. The output of this phase is a resilience curve of Mamuju Port for the Majene Earthquake, which is shown in Figure 61. Based on this figure, we identified four critical changepoints (Table 57) which can help to determine the value of empirical resilience attributes (Table 58). Based on the results of the resilience analysis at Mamuju Port, it was found that the value of port robustness is 0 passengers; port vulnerability is 178 passengers; port responsiveness is 370 days; port rapidity is 57 days, and port recoverability is 3 passengers/day.

Section 6.3 explains the implementation of the port resilience evaluation method in the third phase. The analysis in this phase focuses on the impact of the Majene Earthquake on (1) the socio-technical components at Mamuju Port; (2) the connectivity at Mamuju Port; and (3) the connectivity of ports serving crossings to East Kalimantan Province using the hinterland network on Sulawesi Island. To determine the impact of the disaster on the socio-technical components at Mamuju Port, the best public data that could be used is report data from official institutions, such as PT. ASDP Indonesia as the port operator, or impact evaluation data issued by the National Disaster Management Agency (BNPB). However, these two types of reports were not available in this case.

Therefore, we used data on the coverage of the earthquake impact that we collected from the media. Based on this data, we classified the information into technical and social aspects. The output is in the form of damage assessment results for technical aspects (Figure 62), social aspects (Figure 63), and also a summary of the overall damage to the socio-technical components that affect port operations (Figure 67). Based on the results of this analysis, it was found that the technical components of the port were more affected by the earthquake than the social components. Of these technical components, the most severely affected were the berths and trestles on the sea side, and the passenger terminal on the land side.

In addition, Section 6.3 also studied the impact of the Majene earthquake on Sulawesi Island's connectivity, particularly focusing on the role of Mamuju Port. The immediate impact of the earthquake was primarily single-vertex, with physical infrastructure damage confined to Mamuju Port. However, regarding usable spare capacity, a significant reduction was observed at Pantoloan Port, dropping to 70% of Mamuju Port's required capacity. This decline is attributed to the repurposing of Pantoloan Port as a humanitarian aid transshipment hub, diminishing its spare capacity for Mamuju Port's operations. Furthermore, the Majene earthquake disrupted road access connecting Mamuju Port to alternative ports. The Poros Mamuju-Majene road, which links Mamuju Port to Pare-Pare Port, was rendered impassable due to landslides on both main lanes. Meanwhile, the Poros Mamuju-Palu road, connecting Mamuju Port to Taipa and Pantoloan Ports in Central Sulawesi, was reduced to a single lane, causing traffic congestion as vehicles alternated use of the remaining lane.

To assess the impact of the Majene earthquake on shipping connectivity from Mamuju Port, we analyzed the changes in edges of the transport network following the port's closure. During the response phase, ships from Panajam Port diverted their routes to Balikpapan Port to optimize shipping costs, often subsidized by the government through the Public Service

Obligation (PSO) scheme. Passengers consolidated at Balikpapan Port were then directed to Pare-Pare Port in South Sulawesi, given its adequate spare capacity and closer hinterland proximity. Voyages from Samarinda split between Balikpapan, Pantoloan, and Taipa Ports, reflecting the commercial vessels' strategies to determine the most efficient rerouting while awaiting permits from the Ministry of Transportation through the SIMLALA platform.

During the recovery phase, changes in maritime connectivity became more apparent. Ships from Penajam, primarily PSO vessels, immediately redirected their routes back to Mamuju Port. This swift resumption was facilitated by the strong legal framework mandating PSO vessels to serve Mamuju Port. However, the return of ships originating from Balikpapan was more gradual. Commercial vessels still required rerouting permits and could not immediately resume service to Mamuju Port.

Section 6.4 covers the implementation of the fourth phase of the empirical resilience analysis method, namely resilience intervention analysis. For this phase, the best data can be obtained from primary sources, such as interviews with port operators (PT. ASDP Indonesia) and relevant stakeholders, regarding the strategies employed for disaster management. However, due to the unavailability of such data, we utilized information from various local and international media outlets that discussed mitigation and disaster management efforts at Mamuju Port following the Majene earthquake.

The media articles were analyzed qualitatively using content analysis. Articles were chronologically ordered, and interventions were classified based on the phases of the resilience cycle (preparation, response, recovery, and adaptation). The output of this phase is a comprehensive list of interventions implemented during each phase. During the preparation phase, no specific interventions were identified for mitigating the earthquake's impact in the analyzed media articles or the Mamuju Port Master Plan (RIP) published by the Ministry of Transportation of the Republic of Indonesia.

In the response phase, Table 66 provides a detailed list of interventions implemented to enhance Mamuju Port's resilience. PT. ASDP Indonesia prioritized the immediate repair of earthquake-damaged infrastructure. However, bureaucratic complexities and the COVID-19 pandemic hindered progress. These factors prompted PT. ASDP Indonesia Mamuju Branch temporarily allocates human resources to Balikpapan Port, leading to a stagnant repair process. Repair efforts intensified once COVID-19 subsided, but the total response phase extended to 370 days.

In the recovery phase, with the repair of Mamuju Port's sea-side infrastructure complete, the port operator collaborated with PT. ASDP Indonesia Balikpapan Branch, a ferry service provider, to resume ferry services between Balikpapan and Mamuju Ports. Additionally, efforts were made to inform shipping companies, including private and PSO pioneer vessels, and the general public through official information channels such as the official website, social media, and media coverage, that the sea-side infrastructure at Mamuju Port had been fully repaired. In the adaptation phase, PT. ASDP Indonesia Mamuju Branch focused on repairing land-side infrastructure, such as the passenger waiting terminal. Collaboration with the Indonesian National Armed Forces (TNI) and the Indonesian National Police (Polri) led to the establishment of a task force stationed in the port area to mitigate potential disruptions that could hinder port operations in the future, including natural disasters such as earthquakes.

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7 Reflection on the Method

The previous three chapters have shown the implementation of the port resilience evaluation method developed in three different port case studies. The implementation of the method consists of four phases, each providing unique insights and challenges. This chapter will give a cross-case study reflection to provide a basis for generalizations for other ports in Indonesia that have similar or comparable characteristics to the case study objects, which would be around 80.8% ports from a total of 3,224 ports in Indonesia. In addition, this reflection chapter also serves to provide insight into whether the method can be implemented and generalized for port types beyond those of the three case studies, such as specialized ports (e.g., fisheries, oil, and gas), whose proportion is 18.8% of all ports, as well as Indonesia's leading international ports. The reflection focusses on the data requirement for analysis and the method implementation process, as these two aspects determine the quality of the evaluation results and lessons learned.

7.1 Reflection on Method's Data Collection

This section reflects on the data collected as input for the analysis. The discussion in this section will provide insight into how to deal with the challenges of searching and collecting data in port contexts with different characteristics. Reflections related to the data collection will be discussed per phase of the proposed method. Reflections related to data collection are analyzed using four criteria: data availability, completeness, accuracy, and timeliness. Cross-case reflection on data collection from the three different case studies will be described in each phase.

In the first phase, three distinct sub-analyses were conducted: an examination of ports as socio-technical systems (1), an investigation of port-hinterland connectivity (2), and a study of port shipping connectivity (3). In this discussion, the sub-analyses denoted as (1), (2), and (3), respectively. The three analyses were successfully conducted using the data obtained by the researcher. The data collected for each case study in Phase 1 is presented in Table 67. The data collection process to implement the first phase revealed that the official documents were sufficiently comprehensive to support the execution of sub-analysis (1) and sub-analysis (2) of the Pantoloan and Seba Port. These official documents were obtained from Indonesian Central Statistics Agency (BPS), local government statistics reports, and from the Ministry of Transportation of thr Republic of Indonesia. Given the considerable volume of official data, both public and non-public, supplementary information from press articles was used only to address minor gaps in the data set. Mamuju Port has very limited official public documents, so sub-analysis (1) and sub-analysis (2) require primary data to be able to perform high-quality analysis.

However, the official documents and press articles analyzed for Pantoloan and Seba Port have limitations in terms of data completeness. For example, official documents of Pantoloan Port only provide complete data related to the technical components of the port, but there is no data related to the social components. To overcome this, site visits or requests for internal documents are made to the port operator or authority. The limitation is that this internal data is not available to the public and requires high-level authority access (i.e. officials from the Central Government). Relying on internal data in this phase one analysis can potentially cause research delays because it takes a long time (1-3 months) from the time of the request to conduct the interview until the interview can be carried out.

Concerning sub-analysis (3), the three case studies used data from disparate sources rather than in a uniform manner. For Pantoloan Port, the data utilized primarily consisted of data obtained from AIS and INAPORTNET. Data from AIS provides an advantage in the accuracy of describing ship visits to ports, but there are shortcomings in covering small Indonesian ships or those that do not have AIS installed. To overcome this, data from INAPORTNET is used because it is more complete. However, accessing INAPORTNET data requires obtaining permits from the Ministry of Transportation, which requires a waiting period of 2-4 weeks.

For Seba Port, the data obtained were from the SIMLALA Dataset from the Ministry of Transportation and internal port call records. Data from SIMLALA is publicly available and can be used for research with permission from the Ministry of Transportation. SIMLALA data has a complete coverage of shipping routes per ship, but it can be said that it is not very accurate because the dataset is still in the form of a Ship Operation Plan (RPK) which can be different from its execution. To overcome this, we cross-checked with internal port call records. This data is accurate and complete, but it is not publicly available and takes a long time to obtain it from the first formal request (around 3–4 months).

Mamuju Port's data were entirely based on official data from internal port sources. We did not find any secondary data in the form of official documents that could be used to conduct sub-analysis (3) at Mamuju Port. One way that can be used is by taking the schedule data available on Ferrizy (a passenger ship ticketing purchase portal). In this sub-analysis we rely on primary data derived from interviews and internal port records. These internal port records have a high level of accuracy and are complete, but it takes around 4–6 months to arrange the permits to access them.

Reflecting on the quality of the data collected above, there is sufficient publicly available data and access to official sources to conduct sub-analysis (1) and (2). However, much of this data is still aggregated and considered incomplete for analysis on a smaller disaggregated scale (e.g. daily or weekly). This is a note for the government so that it can provide statistics or public data in the form of a disaggregated scale with smaller dimensions of analysis. As a consequence, currently for researchers or non-governmental organizations, ensuring direct access to stakeholders or managers is highly recommended to obtain detailed non-aggregated data, especially for the social component and the interaction of socio-technical components in shaping port operations as long as these non-aggregated data are not publicly available.

To facilitate non-government parties in conducting the entire analysis of phase 1, the government or port manager can enrich the data on social components and socio-technical interactions using the port master plan or port profile to improve the data collection for sub-analysis (1) and (2). In comparison, sub-analysis (3) shows that this part of the analysis requires different data for each context. Large ports with high container traffic, such as Pantoloan Port, have easier access to real-time monitoring traffic flows, such as AIS data. Meanwhile, Seba Port and Mamuju Port, which are smaller, non-container ports, need access to publicly available traffic datasets. To improve data access for sub-analysis (3), the government and relevant stakeholders could accelerate the implementation of information systems, equalize the format of traffic recording datasets, and create procedures for accessing datasets of ship visits at non-container ports in Indonesia.

Table 67. Reflection of data collection on the implementation of Phase 1

Port	**Phase 1: Port System and Connectivity Analysis (Pre-Disaster)**	
	Data Collected	**Reflection on Data Quality**
Pantoloan Port (Commercial, Managed by State-Owned Enterprise, Container Terminal Focused, Large-Sized Ports)	**Socio-Technical System Analysis**	
	• Official documents; Press Articles; Field Visits Report; Interview Transcript	• Secondary data was publicly available and could be used to accurately map the technical components. To accurately determine the social components and interactions between components, primary data was needed through interviews and field visits. The time to arrange permits to access primary data was around 1 month.
	Ports-Hinterland Connectivity Analysis	
	• Official documents	• All data was publicly available. The data was obtained from official institutions such as the Ministry of Transportation, BPS, local governments, and the Geospatial Information Agency. The combination of these four documents produced an accurate and complete dataset for analyzing the ports-hinterland network.
	Port Shipping Connectivity Analysis	
	• AIS Dataset; BPS Document; INAPORTNET Dataset	• The BPS data was publicly available and accessible, but it only included aggregate data per port and did not show ship routes. Port traffic datasets and non-aggregate routes for analysis can be obtained using AIS, but the cost of accessing AIS is expensive and does not cover small ports and ships. More complete and accurate data can be obtained from INAPORTNET, but it takes 2–4 weeks to obtain the access permit.
Seba Port (Non-Commercial, managed by the Government, General Cargo Focused, Medium-Sized Ports)	**Socio-Technical System Analysis**	
	• Official Documents; Press Articles; Interview Transcript	• Secondary data was publicly available and could be used to accurately map the social components. To accurately determine the technical components and interactions between components, primary data was needed through interviews and field visits. The time to arrange permits to access primary data was around 3 months.
	Ports-Hinterland Connectivity Analysis	
	• Official Documents; Interview Transcript	• Secondary data was publicly accessible. A combination of secondary data from the BPS, Ministry of Transportation, and local government can be used to conduct an accurate analysis. Data that was not updated is data on the number of truck fleets. Interviewing stakeholders is necessary to confirm the number of truck fleets and Tardamu Airport capacity available in the Sabu Raijua area. The interview data is accurate, but the interview request takes 2 months to be carried out.
	Port Shipping Connectivity Analysis	
	• SIMLALA Datasets; Internal data records; Interview Transcript	• SIMLALA datasets can be accessed with permission from the Ministry of Transportation. This dataset can be used to map port connectivity including the routes of ships visiting ports. This dataset has a weakness in accuracy because it was still in the form of a route plan. Interviews/internal data can be used to validate the accuracy of SIMLALA data, but the interview request takes 2 months to be carried out.

Table 67 Continued

Port	**Phase 1: Port System and Connectivity Analysis (Pre-Disaster)**	
	Data Collected	**Reflection on Data Quality**
Mamuju Port (Commercial, Managed by State-Owned Enterprises, Passenger Focused, Small-Sized Ports)	**Socio-Technical System Analysis**	
	• Official Documents; Media Article; Interview Transcript	• The official documents for this sub-analysis were very limited, and the details of the technical components are mostly found in press articles. Interviews are needed to map the socio-technical components and their connections. Interview requests take 6 months to be carried out.
	Ports-Hinterland Connectivity Analysis	
	• Official datasets; Official Documents	• Data on road sections connecting passenger ports in West Sulawesi is available online from multiple official sources and is updated regularly. This dataset is also accurate because it is verified directly by state agencies and is complete, covering all types of roads, from major roads (which can be used by passenger buses) to small roads that cannot be used by buses or large vehicles. The data can be requested and downloaded at any time. Data on the number of ports, fleets, and port capacity was obtained in complete from the central and regional statistical reports as well as transportation statistics from the Directorate General of Land Transportation of the Republic of Indonesia.
	Port Shipping Connectivity Analysis	
	• Online ticketing platform dataset; Internal Document; Interview Transcript	• Secondary data can be retrieved from the online ticketing platform to find out the routes of ships serving Mamuju port. However, canceled or changed schedules are not covered in this dataset. Confirmation is needed through interviews or studying primary data sources to perform a more accurate and complete analysis. The time required to request data until internal data is obtained is 6 months.

In the second phase, data was collected to plot the resilience curve. Table 68 shows the data collected and the quality of the data collected to implement phase 2. The following notes were made based on the data collected for each case study. Data related to ship cargo loading and unloading is the ideal data to develop the resilience curve. Unfortunately, due to the confidentiality of the data and the security of the port's business processes, no port operator wanted to share that data. So, the only option was to study the ship port visit data and calculate the theoretical capacity of the ships, assuming a full load for each ship. Based on our experience conducting the analysis, we found that for large container ports, such as Pantoloan, the analysis benefits from external data not tied to institutions and licenses, such as AIS datasets. This contrasts with medium-sized or minor non-container ports where obtaining publicly available vessel visit data is difficult. Thus, reliance on confidential internal port records is very high for smaller ports.

Accurate ship visit data is a prerequisite for implementing phase 2. Phase 2 cannot be carried out if data related to ship visits (and, ideally, what they contain) cannot be found. The government, as the data owner, can carry out the analysis in phase 2. However, researchers or institutions outside the government who want to implement phase 2 need to ensure they have clearance and permission to access the data. Suppose the government wants to facilitate the implementation of phase 2. In that case, it is necessary to provide a legal basis for information disclosure regarding the type and volume of cargo carried by ships at ports in Indonesia. This initiative has already been started with the development of SITOLAUT, which records the types of cargo carried by ships on sea toll routes (the government's freighter subsidy program for remote areas in Indonesia). However, this information is still limited in describing the type of cargo and needs to be more detailed in terms of the freight volume. The policy that can increase transparency of cargo throughput could make resilience curve plotting easier, because it can find out the level of port resilience in handling certain goods or commodities compared to ship visits or capacity, the results of which are more often needed by outer islands.

Table 68. Reflection of data collection on the implementation of Phase 2

Port	**Phase 2: Resilience Curve Analysis**	
	Data Collected	**Reflection on Data Quality**
Pantoloan Port	• AIS Dataset (August 2018 - August 2019); INAPORTNET Dataset (August 2018 - 2019)	• AIS data was publicly available but it required a considerable cost to access it. AIS data is accurate but has limitations for accessing ports and small vessels. Data from INAPORTNET has complete data records for ports in Indonesia, for both large and small vessel traffic. However, INAPORTNET data takes about 1 month to obtain access permission. Both types of datasets do not explain the type and volume of cargo unloaded and loaded at ports.
Seba Port	• Internal Port Call Data (January 2021 - January 2022); Ship Operational Plan Dataset SIMLALA (January 2021 - January 2022)	• The SIMLALA Ship Operating Plan dataset was publicly available with permission from the Ministry of Transportation. The complete SIMLALA dataset shows ship routes as the basis for port call calculations, but is lacking in accuracy because it is still in the form of an operational plan. Internal port call data is still needed to perform an accurate resilience curve analysis. However, obtaining this data takes about 3 months to get access permission.
Mamuju Port	• Internal Port Call Data (September 2020 - December 2022); Ship Schedule Dataset (September 2020 - December 2022)	• It was difficult to find official secondary documents containing port calls in disaggregated form. The only one available and accessible to the public is the ship's departure schedule from the online ticketing system platform. The dataset from the online platform is very accurate for normal port conditions. However, the dataset from this platform cannot represent post-disaster scheduling and service conditions. For this reason, internal port call data was needed so that the analysis can be more complete and accurate. However, the time needed to obtain this internal data takes 6 months from the request to the data being obtained.

In the third phase, the implementation of the method also involves the three sub-analyses used in the first phase These sub-analyses in phase three focus on the conditions after the disaster. In this third phase, we found that sub-analysis (1) and (2) can use data from mass media covering port conditions and the affected port's hinterland network. Mass media data has advantages, including the speed of publication so that it can be directly used for analysis. Regarding quantity, most press articles covered Pantoloan and Mamuju Ports. This is because both ports have essential national and regional roles. National mass media covered Pantoloan port, while local press covered Mamuju port. In addition, there were also several official reports on the field conditions after the disaster that were complete for Pantoloan, but the publication time was several months after the disaster.

On the other hand, the situation for Seba Port was harder to assess, due to its location on a remote island and limited access to coverage. For sub-analysis (3), Pantoloan Port relied on AIS datasets, Seba Port relied on internal port documents, and Mamuju Port relied on datasets from online ticketing that showed changes in shipping schedules. More details about the data collected and data quality in phase 3 are shown in Table 69.

Table 69. Reflection of data collection on the implementation of Phase 3

Port	**Phase 3: Disaster Impact Analysis**	
	Data Collected	**Reflection on Data Quality**
Pantoloan Port (Commercial, Managed by State-Owned Enterprise, Container Terminal Focused, Large-Sized Ports)	**Socio-Technical System Analysis**	
	• Official field reports; Independent Field Reports; Press Articles	• A lot of data was publicly available regarding the socio-technical component of Pantoloan Port after the disaster. Accurate and complete information about the post-disaster condition of the port can be obtained by cross-checking official field reports, reports from independent institutions, and press articles. Information about the social component can be obtained from official field reports.
	Ports-Hinterland Connectivity Analysis	
	• Official field survey reports; Press articles	• There were many direct field survey results related to the condition of roads damaged by the earthquake, especially from the Ministry of Public Works and Housing which are updated daily. Press articles are used to cross-check the condition of connecting roads between ports, from the time they are first affected until the road is completely repaired. This cross-checking of secondary data provides a complete and accurate picture of post-disaster conditions related to ports-hinterland connectivity. The data was also publicly available and can be used directly for analysis.
	Port Shipping Connectivity Analysis	
	• AIS Dataset; Press Articles	• The AIS dataset can be used to accurately map post-disaster ship traffic. However, coverage is limited to large ships only, so small ships and humanitarian ships are not explicitly recorded. To improve data completeness, data from press articles is used, specifically to determine the visits of humanitarian ships to Pantoloan port.
Seba Port (Non-Commercial, managed by the Government, General Cargo Focused, Medium-Sized Ports)	**Socio-Technical System Analysis**	
	• Focus Group Discussion Transcript; Press articles	• The availability of press articles that explain the socio-technical system conditions in Seba Port is very limited and few. Hence a focus group discussion was held, facilitated by the Ministry of Transportation to find out the socio-technical conditions of the Seba Port after the disaster. The data was considered accurate and complete according to the views of the experts who participated in the focus group discussion.
	Ports-Hinterland Connectivity Analysis	
	• Official Documents; Interview Transcript; Press Articles	• Official documents from the Ministry of Public Works and Housing provide a detailed and accurate update on the condition of the roads on Sabu Island. However, the condition of the truck fleet and the decision to drive trucks after the disaster requires validation through interviews with relevant stakeholders (port operators or truck drivers who was working after the disaster).
	Port Shipping Connectivity Analysis	
	• Internal Official Document	• No secondary data was found explaining the changes in port shipping connectivity after the disaster at Seba Port with good accuracy and completeness. The analysis relies on internal records from Seba Port. The internal data was considered accurate and complete by the port operator. However, accessing this internal data takes a long time (2–3 months from request to retrieve of data).

Table 69 Continued

Port	Phase 3: Disaster Impact Analysis	
	Data Collected	**Reflection on Data Quality**
Mamuju Port (Commercial, Managed by State-Owned Enterprises, Passenger Focused, Small-Sized Ports)	**Socio-Technical System Analysis**	
	• Press Articles; Internal Official Document	• The coverage of press articles related to the condition of the technical components of Mamuju port was quite accessible to the public, accurate, and complete. However, to find out about the social components, access to the company's official internal data is required. This internal data records who are the employees and what departments are affected by the disaster.
	Ports-Hinterland Connectivity Analysis	
	• Press Articles; Interview Transcript	• Official data documents that accurately and completely describe the post-disaster conditions of the hinterland in West Sulawesi were not found. Thus, this analysis was conducted using data from press articles. The analyzed press articles data covered the post-earthquake conditions of the hinterland, including the condition of roads blocked by landslides or damaged, alternative ports serving as the entrance to West Sulawesi, and the condition of the bus fleet after the disaster. To validate the results of the analysis with stakeholders, it took 6 months to obtain permission to conduct interviews.
	Port Shipping Connectivity Analysis	
	• Online ticketing platform dataset	• Secondary data in the form of schedule datasets from online ticketing platforms such as RoroPrahu Hub and Ferrizy was used for analysis. This dataset was used as an alternative due to the absence of official documents explaining the post-disaster shipping connectivity conditions. The two datasets were used and cross-checked to show shipping traffic at Mamuju Port to be complete and accurate. The collection of primary data was constrained by the absence of sources or experts who were able to recall the details of the post-incident situation in details. No internal documents were found or available to analyze changes in shipping connectivity.

The third analysis phase focused on how the disaster impacted the port and the surrounding transportation network. Thus, the minimum data required is the level of technical damage for the port, the port-hinterland network, and the shipping network. Press articles are a handy source of data because they are widely available and can show how the condition of the port and the surrounding transportation network for the period right after the disaster. We found many press articles discussing the disaster impact on the port and the disaster impact for sub-analysis (1) and (2). Although much data may be available, the press article data must be appropriately scrutinized and curated from trusted media. There may be a lot of data available, but the accuracy of the data is not always guaranteed. What the government or port manager can do to improve this, is to make an official situational report that is released to the public as accurately and quickly as possible so that sub-analysis (1) and (2) can be carried out. This is especially important for remote ports with little press coverage.

For sub-analysis (3), apart from Pantoloan Port, the other two ports are very dependent on access to internal data , and there are no press articles that can help the analysis because the number is minimal. Using data on ship visits and loading and unloading traffic, sub-analysis (3) can be conducted. Sub-analysis 3 is the costliest part due to the difficulty of obtaining data. For ports not covered by AIS, the internal port should be able to provide a record of the port traffic after the disaster. For this reason, the government, as the regulator of public and commercial ports managed by state-owned enterprises, can create a backup information system that is disaster-resistant to continue recording port productivity even when it is affected by disasters so that sub-analysis (3) can be carried out more quickly and accurately.

Phase four focuses on finding out what interventions are made by the stakeholders. Accurate analysis results from phase 2 (resilience curve analysis) were used as a reference for the timeline for this analysis. In addition, the results from phase 3 illustrate the severity of the impact of the disaster and how it affects the interventions to improve port resilience. Pantoloan Port and Seba Port have official documents and field survey reports explaining what efforts were made in the response, recovery, and adaptation phases, which are complete, as well as many available press articles that can be used as a complement. Meanwhile, data from Mamuju Port is only available from press articles due to the lengthy process needed to gain access to the Mamuju Port primary data. The preparation phase (pre-disaster) is the phase with the most challenging data acquisition, both primary and secondary. This indicates that planning to mitigate and respond to disasters has to be well thought out during the design and construction phases of the port. The data collected and data quality in phase 4 at each port case study can be seen in Table 70.

As a reflection, the minimum data needed for analysis in phase four is the intervention carried out within the range of the four stages of the resilience curve: preparation, response, recovery, and adaptation. The results of phase 3 analysis are helpful as an additional explanation of the severity of disaster impacts on ports and islands, which ultimately affects the interventions to improve port resilience. The analysis cannot be conducted if the minimum data is unavailable. At the time of this study, complete intervention data was obtained from ports under the authority of the Directorate General of Sea Transportation. The intervention data was presented in various documents, complete with timelines and whether the intervention was carried out at the port or network level, helping the analysis to be carried out more quickly.

The port of Mamuju, under PT ASDP and the Directorate General of Land Transportation, has a lack of clear documentation related to disaster preparation for the port and its island transportation network. This is understandable because the Directorate focuses more on handling land transportation than ferry connections in disaster conditions. This research was helped by the many press articles available for analysis in phase 4. However, if the press articles were not available, then the implementation of phase 4 would be very difficult to implement, and lessons learned would be difficult to obtain. So, researchers who want to implement phase 4 at passenger ports must first check whether the data is directly available or whether the port manager has the data, and whether there are alternatives to getting the data. If neither exists, then the Directorate General of Land Transportation should mandate the ferry port operators under the Directorate General of Land Transport to document various interventions in increasing port resilience, starting from preparation, response, recovery, and adaptation stages.

Table 70. Reflection of data collection on the implementation of phase 4

Port	**Phase 4: Resilience Intervention Analysis**	
	Data Collected	**Reflection on Data Quality**
Pantoloan Port	• Official Field Survey Documents; Press Articles; Official Port Recovery Plan	• The secondary data collected was publicly accessible and available online. The combination of the secondary data obtained accurately and completely describes the various interventions carried out in the preparation, response, recovery, and adaptation phases.
Seba Port	• Press Articles; Official Documents; Expert Interviews Transcript	• Secondary data in the form of official documents and several press articles were publicly accessible and available online. This data can provide an accurate and complete explanation of post-incident interventions (response, recovery, and adaptation phases). For interventions in the preparation phase, data from interviews with stakeholders (port operators) is used to obtain a more accurate and complete picture. Permission to conduct interviews with stakeholders can take 3–6 months to obtain.
Mamuju Port	• Press Articles	• There are many press articles that can be used to analyze post-incident intervention for Mamuju Port, especially in the response, recovery, and adaptation phase. For the preparation phase, no concrete evidence was found about the intervention prepared by the port. Permission to confirm with relevant stakeholders was not obtained, so the analysis relies solely on secondary sources. The accuracy and completeness of the data is only for the post-incident, while the preparation phase needs to be validated again in the future.

7.2 Reflection on the Method’s Implementation Process

In this section, the reflection focuses on the implementation process of the method proposed in this study. The discussion in this section will provide insights related to several things, such as whether the implementation process could be performed according to the initial plan, whether it is possible to accelerate the process, whether the method is appropriate, and whether steps need to be improved in the implementation procedure. Reflections on the implementation process are assessed from criteria related to the ease of implementation and the time necessary to implement the method. The discussion will be stuctured per phase of the method as done in the previous section.

In phase 1 of the implementation, the proposed method could be applied well in all three case studies. The method in phase 1 consists of 3 sub-analyses. The implementation process is relatively easy and quick for the sub-analysis processes (1) and (2) because the secondary official data obtained is sufficient for the analysis task. For Pantoloan Port and Seba Port, the availability of official data that the public can access allows sub-analysis (1) and (2) to be done quickly. A small note on Mamuju Port: The implementation process for sub-analysis (1) and (2) did not go as planned for several reasons. First, there was a lack of publicly available data that could be used for the analysis. Second, at the time of the research, there was the COVID-19 pandemic. This caused the implementation process to take a long time because it was waiting for primary official data from the port manager or the government. For sub-analysis (3), Pantoloan Port was the most accessible port to analyze because of the availability of complete data, where much of the data are sourced from official agency data. However, Seba Port and Mamuju Port took longer than planned due to difficult access to official data. This subsection shows more fully how the method was implemented in each sub-analysis per case study, along with notes related to its applicability.

The following are some reflection notes from the phase 1 implementation process above. We found that the procedures and data processing themselves did not present any problems. Phase 1 focused on conducting a descriptive analysis of the port and the transportation network connected to the port. The biggest obstacle was finding complete, accurate, and full data to perform the phase 1 analysis directly. This is more pronounced when analyzing small or medium-sized ports that are central in the region or outer islands, such as Seba and Mamuju Ports. Phase 1 analysis helps clarify how the context of the port being analyzed can later be used as a lesson for ports with similar contexts.

To accelerate the phase 1 implementation process, the government can complement the port master plan with the port's social components and socio-technical interactions, and update the documents periodically. In addition, the port master plan needs to be completed with data on what alternative ports exist or will be built in relatively proximity to the port. Road network data must be included in the road specification connecting the port with other alternative ports. With these complete and official data, sub-analysis (1) and (2) can be done easily and quickly. For sub-analysis (3), it is necessary to mandate port operators and shipping operators to jointly record accurate data on ship visits, ship cargo, ship volume, and the origin and destination of the ships. Regardless of whether the data will be made public, the existence of such data and its uniform format can be a solution to accelerate the implementation of the method in phase 1. Table 71 shows the reflections related to the implementation and the applicability of the method in phase 1.

In the implementation process of phase 2, the method proposed in this research can generate resilience curves quite well in all three case studies. Table 72 shows the reflections related to the applicability of the evaluation methods in the three case studies. The biggest challenge of the implementation process in this phase is the need for daily ship traffic or ship cargo data in the form of disaggregated data for an extensive period (1 - 2 years). As for data processing itself, such as tidying up the dataset and processing it into a resilience curve, no problems were found. Many open-source programming languages or software tools can aggregate the data into a curve. Implementing the phase 2 method for Pantoloan Port was the easiest and fastest of the three case studies. This is because disaggregated data related to ship visits can be accessed without depending on internal port data, since AIS data is available for the larger ports.

Meanwhile, for Seba Port and Mamuju Port, the dependency on disaggregated data is relatively high compared to a larger port. This dependency hampered the Seba Port and Mamuju Port analysis process and prevented it from going as planned. This was exacerbated by COVID-19, which disrupted the data collection process, especially at Mamuju Port, because, as a passenger port, it had stricter measures to respond to COVID-19.

As a reflection, if port authorities or non-container port managers do not provide disaggregated records of ship visits or cargo, then phase 2 cannot be implemented. For phase 2 to be implemented more easily and quickly in the future, it is unrealistic to assume that these small non-containerized ports will be indexed in AIS, because ports of this type generally have a low economic value. Instead, the government authorities can accelerate the implementation of information systems for recording ship traffic flows at ports, such as INAPORTNET (http://inaportnet.dephub.go.id), and mandate that the data be made public for research purposes. INAPORTNET is a standardized electronic port information system for serving ship visits and loading and unloading goods. When this thesis was written, 264 out of 3,224 ports in Indonesia had already implemented INAPORTNET.

For the implementation process of phase 3, it was found that this method is easily applied to Pantoloan Port because it has secondary data from official institutions, and also significant mass media coverage to conduct sub-analysis (1), (2), and (3) after the disaster. For the comparison between case studies, it was found that sub-analysis (2) is an analysis that can be done quickly due to the availability of data – both data from official institutions and mass media coverage. Sub-analyses (1) and (3) at Seba and Mamuju Ports rely on internal data from ports, which are generally confidential. Table 73 shows the implementation process of phase 3 in each case study, along with its reflections.

On reflection, the implementation process in this phase could have been more fruitful. One obstacle was not the implementation process but gaining access to accurate damage data from official bodies at the port level and transportation networks in non-container ports and small ports. One of the things that can be done to facilitate the application of sub-analyses (1) and (2) in the future is to mandate the Regional Disaster Management Agency to standardize the situational report for port assessment, covering at least two components: the port system itself and the relationship between the port and its hinterland network. Meanwhile, to facilitate the application of sub-analysis (3), it is necessary to develop a national information system for the Ministry of Transportation that can inform changes in ship schedules along with available cargo quotas. The information can be used to analyze changes in the shipping connectivity network after a disaster.

Regarding the implementation process in phase 4, no significant obstacles were found. This is because each port already had (almost) complete secondary data to carry out any interventions by stakeholders. In addition, each case study already had the resilience curve results from the phase 2 implementation results. The role of the resilience curve is crucial as a framework for serving as a staging benchmark for intervention analysis. Official data explaining the responses of related parties can generally be found through ministry press releases and mass media. Table 74 shows the implementation process in each port and the applicability of this method to the three ports.

Table 71. Reflection of the method implementation process of Phase 1

Port	**Phase 1: Port System and Connectivity Analysis (Pre-Disaster)**	
	Method Implementation	**Reflection on Applicability**
Pantoloan Port (Commercial, Managed by State-Owned Enterprise, Container Terminal Focused, Large-Sized Ports)	**Socio-Technical System Analysis**	
	• Secondary data was sought by desk study; Primary data was sought by field study; Data was then analyzed, and the results in the form of Block Diagrams were shown to relevant stakeholders for validation.	• The method can be applied straightforwardly to technical components. The difficulty of implementation lies in the lack of data on social components and interactions between the two components that are open to the public. This situation encourages field visits and interviews, which require a longer process to implement this method.
	Ports-Hinterland Connectivity Analysis	
	• Secondary data was sought by desk study and was completed to analyze the values of SC_p, dt_p, and $N_p(t)$ which are the main outputs of this analysis	• The method can be implemented directly because the secondary data needed for calculating SC_p, dt_p, and $N_p(t)$ were already complete and accurate. The data needed to calculate the equation can be seen in section 3.2.1
	Port Shipping Connectivity Analysis	
	• Secondary data is complete to conduct the analysis to determine the port connectivity value, C_{ij} and inbound - outbound connectivity of the port under study.	• The method can be implemented directly as the required secondary data is widely available for corroboration. Implementing the method requires additional time if the researcher does not have the skills to process large datasets (i.e., using Python).
Seba Port (Non-Commercial, managed by the Government, General Cargo Focused, Medium-Sized Ports)	**Socio-Technical System Analysis**	
	• Secondary data was obtained from a desk study, and primary data was obtained by interviewing stakeholders. The data obtained is then processed into a Block Diagram.	• The method can be applied straightforwardly to social components. The difficulty of implementation lies in the lack of data on technical components and interactions between the two components that are open to the public. This situation encourages interviews to validate the analysis, which require a longer process to implement this method.
	Ports-Hinterland Connectivity Analysis	
	• Secondary data was obtained from desk study; Primary data was obtained by interviewing stakeholders related to Truck drivers and situation on Tardamu Airport. The completed data is analyzed to get the values of SC_p, dt_p, and $N_p(t)$.	• The implementation of the method took longer because one of the port alternatives was an airport (Tardamu Airport) where secondary data was very limited. In addition, secondary data on the truck fleet on Sabu Raijua Island was also incomplete, so the calculations of SC_p, dt_p, and $N_p(t)$ and were slightly hampered. These two data were sought through interviews, which made the method implementation process take longer.
	Port Shipping Connectivity Analysis	
	• Secondary data was obtained through a desk study but was incomplete; primary data in the form of internal port call records and interviews were conducted to obtain missing data. The complete data was then analyzed to determine the port connectivity value C_{ij} and the inbound-outbound connectivity capacity of the ports studied.	• The secondary data obtained from SIMLALA is still in the form of a shipping plan, so more accurate primary data is needed to perform the analysis. The implementation of the method takes longer because accurate and publicly available secondary data is not available, and also if the researcher does not have the skills to process large datasets (i.e., using Python).

Table 71 continued

Port	Phase 1: Port System and Connectivity Analysis (Pre-Disaster)	
	Method Implementation	**Reflection on Applicability**
Mamuju Port (Commercial, Managed by State-Owned Enterprises, Passenger Focused, Small-Sized Ports)	**Socio-Technical System Analysis**	
	• Secondary data was obtained by desk study; Primary data and internal company data were obtained through access to the government. The complete data is then processed into a Block Diagram	• The publicly accessible secondary data was very limited (only covering technical components), making the analysis method cannot be applied directly. The analysis took 2 months longer than for other ports because it relied on primary data from Mamuju port stakeholders to apply the analysis method.
	Ports-Hinterland Connectivity Analysis	
	• Secondary data is obtained from the desk study and has been completed to be analyzed to get the values of SC_p, dt_p, and $N_p(t)$.	• The method can be directly applied to calculate the values of SC_p, dt_p, and $N_p(t)$ because the secondary data obtained is publicly available, accurate, and complete. No significant obstacles were found in applying this analysis method to Mamuju Port.
	Port Shipping Connectivity Analysis	
	• Primary data is obtained from relevant stakeholders through internal document records and secondary data from ferry schedule and ticketing platform datasets, then analyzed to determine the port connectivity value C_{ij} and the inbound-outbound connectivity capacity of the ports studied.	• The limitations of secondary data make the method not directly applicable and require access to primary data sources. The available secondary data was data that can be viewed from the online ticketing platform showing the ferry departure schedule from the port of origin to the port of destination. Permission from stakeholders was required to obtain the dataset in a structured and analyzable form. The implementation of this method at Mamuju Port takes a long time due to this bureaucratic process and also the processing of permits to obtain primary data from port operators.

Table 72. Reflection of the method implementation process of Phase 2

Port	Phase 2: Resilience Curve Analysis	
	Method Implementation	**Reflection on Applicability**
Pantoloan Port	• The data from AIS and INAPORTNET was tidied up for analysis, then the *CVC* metrics were calculated in the form of daily vessels visit. The resilience curve is plotted using Python Libraries.	• Pantoloan Port had complete and accurate port call records from AIS and INAPORTNET. However, accessing AIS required a high cost (> EUR5,000), while INAPORTNET required a paperwork process that takes up to 1 month. As long as this data is not obtained, the method cannot be implemented directly. When the data was received, the implementation of this method was quite straightforward, namely calculating the daily ship visits with the CVC metric and plotting it in the form of a resilience curve. The ability to process large datasets (i.e. using Python) was very helpful in shortening analysis time spent.
Seba Port	• Data from internal port calls and Ship Operating Plans (Rencana Pengoperasian Kapal - RPK) from SIMLALA from January 2021 to January 2022 were obtained with academic permission from stakeholders to be directly analyzed into CVCCargo metrics to create a resilience curve.	• The secondary data that can be accessed to directly implement the analysis method at Seba Port was the ship operation plan (SIMLALA) from Ministry of Transportation. SIMLALA contains daily shipping plan data for Indonesian-flagged ships. This data requires permission from the Ministry of Transportation to be used in academic research. However, the downside is that the data is still in plan form and requires validation by internal stakeholders or internal port data. Complete and accurate data was finally obtained from cross-checking data from internal port calls and SIMLALA data. This dataset was then tidied up for CVC_{Cargo} calculation analysis and resilience curve plotting. The ability to process large datasets (i.e. using Python) was very helpful in shortening analysis time spent.
Mamuju Port	• Data from internal port call and ferry schedule datasets from September 2020 to December 2022 were used to calculate Passenger Vessel Capacity, PVC, to plot the resilience curve.	• The method implementation at Mamuju Port was the most difficult compared to other case studies. This challenge was due to the difficulty of finding secondary data that could be used to calculate the daily Passenger Vessel Capacity (in the form of disaggregated data) visiting Mamuju Port. The online ticketing platform can be used, but it is limited to the period before a disaster incident or normal conditions. The method application process at Mamuju Port takes a long time because it takes up to 6 months to wait for a response and permission to provide internal data. The ability to process large datasets (i.e. using Python) was very helpful in shortening analysis time spent.

Table 73. Reflection of the method implementation process of Phase 3

Port	**Phase 3: Disaster Impact Analysis**	
	Method Implementation	**Reflection on Applicability**
Pantoloan Port (Commercial, Managed by State-Owned Enterprise, Container Terminal Focused, Large-Sized Ports)	**Socio-Technical System Analysis**	
	• The desk study sought secondary data; all secondary data was then analyzed using the PIDA and Post-Disaster Block Diagram.	• There is a lot of secondary data related to reports and updates on the post-disaster situation in Pantoloan Port that is directly accessible and open to the public, consisting of official reports, independent field reports, and press articles. This secondary data covers the technical and social components conditions of the port after the disaster. Because the secondary data is complete, the analysis can be done directly and straightforwardly.
	Ports-Hinterland Connectivity Analysis	
	• Secondary data were obtained through desk study; Primary data were collected through interviews to complete the missing information. The complete data is then analyzed to get the value of SC_p, dt_p, and $N_p(t)$ after the disaster.	• Data related to the condition of road damage connecting Pantoloan port with other ports is publicly available from various sources. However, to calculate SC_p, dt_p, and $N_p(t)$, calculations related to changes in the number of truck fleets in the area are also required. Changes in the number of trucks are not available in secondary data and need to be confirmed with stakeholders, especially local governments. Knowing the change in the number of truck fleets makes calculating the values of SC_p, dt_p, and $N_p(t)$ straightforward and reduces the time needed to implement the method.
	Port Shipping Connectivity Analysis	
	• The AIS dataset and press articles was directly analyzed to determine the port connectivity value C_{ij} and the inbound-outbound connectivity capacity of the studied ports after the disaster. The resilience curve resulting from phase 2 was used for the division of the shipping connectivity change analysis phase.	• The AIS dataset obtained was used to analyze changes in port shipping connectivity at Pantoloan Port. Data from press articles was used to map changes in connectivity involving small and humanitarian ships visiting Pantoloan Port. This combined dataset and press articles were then processed using Python to calculate C_{ij} after the disaster. The ability to process large datasets (i.e. using Python) was very helpful in shortening analysis time spent.
Seba Port (Non-Commercial, managed by the Government, General Cargo Focused, Medium-Sized Ports)	**Socio-Technical System Analysis**	
	• Primary data was taken from focus group discussion participants who visited Seba Port after the disaster. Secondary data was sought by desk study; all data obtained was analyzed using PIDA and Post-Disaster Block Diagram.	• The secondary data that can explain the socio-technical conditions of Seba Port after the disaster is very limited. There are also very few press articles reporting on Seba Port after the disaster. These limitations make the direct implementation of the method difficult. Data collection was then carried out by holding an online focus group discussion (FGD) (because at that time it was COVID-19 so it was not possible to conduct an FGD in person). The FGD participants were attended by parties who had visited Seba Port after a natural disaster, to develop PIDA and Post-Disaster Block Diagram together. The time needed to invite and gather resource persons for the FGD was 2 months.
	Ports-Hinterland Connectivity Analysis	
	• Secondary data is obtained from a desk study; primary data is taken through interviews to complete the information needs that are still lacking. The complete data is then analyzed to get the value of SC_p, dt_p, and $N_p(t)$ after the disaster.	• Official documents from the Ministry of Public Works and Housing can be used to analyze changes in the capacity of the roads connecting Seba Port with other ports. Other secondary data needed to calculate SC_p, dt_p, and $N_p(t)$, such as changes in capacity at Tardamu Airport and changes in the availability of the cargo truck fleet, require access to primary data. The time required to arrange for permission to access this primary data is around 2–3 months.

Port	**Phase 3: Disaster Impact Analysis**	
	Method Implementation	**Reflection on Applicability**
	Port Shipping Connectivity Analysis	
	• Primary data of post-disaster port call records were obtained through the Directorate General of Sea Transportation, Ministry of Transportation of the Republic of Indonesia. This data is then used to determine the port connectivity value C_{ij} and the inbound-outbound connectivity capacity of Seba port after the disaster.	• The method cannot be applied directly because there is no secondary data that can be used to see changes in port shipping connectivity. To apply this method, data on post-disaster ship visit records is needed. This data is obtained from the Central Government through the Ministry of Transportation in the form of limited access internal post-disaster port call data. It takes an additional 2-3 months to obtain this post-incident port call data. When the internal port call data has been obtained, the C_{ij} calculation can be carried out immediately. Resilience curve results from phase 2 are used for the division of the shipping connectivity change analysis phase.
Mamuju Port (Commercial, Managed by State-Owned Enterprises, Passenger Focused, Small-Sized Ports)	**Socio-Technical System Analysis**	
	• Secondary data is obtained through desk study; Primary data is obtained by interviewing the port authority (UPP Class III Mamuju) to complete the information. All complete data is analyzed using PIDA and Post-Disaster Block Diagram.	• The publicly accessible secondary data was very limited (only covering technical components), making the analysis method cannot be applied directly. The analysis took 2 months longer than for other ports because it relied on primary data from Mamuju port stakeholders to apply the analysis method.
	Ports-Hinterland Connectivity Analysis	
	• Secondary data were obtained from desk study; primary data were taken from port authority interviews (UPP Class III Mamuju) to validate some assumptions. The complete data were then analyzed to obtain the post-disaster values of SC_p, dt_p, and $N_p(t)$.	• The analysis method for calculating post-disaster changes of SC_p, dt_p, and $N_p(t)$ cannot be done directly due to limited secondary data, which only data on changes in the capacity of port connecting roads obtained through press articles. The data on changes in the capacity of alternative ports and changes in the number of bus fleets require additional time to retrieve for direct validation with stakeholders, which takes an additional 6 months. When the data needed for analysis was complete, the values of SC_p, dt_p, and $N_p(t)$ can be calculated directly.
	Port Shipping Connectivity Analysis	
	• Secondary data was obtained from the dataset of changes in ferry departure schedules; the data is used as the main reference in determining the value of port connectivity C_{ij} and the capacity of inbound - outbound connectivity of Mamuju port after the disaster. Resilience curve results from phase 2 are used for the division of the shipping connectivity change analysis phase.	• Data on changes to shipping schedules from online ticketing platforms (Ferrizy and RoroPrahu Hub) is used as the basis for analyzing post-disaster port shipping connectivity. The data from this online ticketing platform needs to be tidied up first so that it is ready for analysis. In addition, permission is required to use the data for research purposes. The ability to process large datasets (i.e. using Python) is very helpful in shortening the analysis time. The resilience curve results from phase 2 are used to divide the analysis phases of shipping connectivity changes.

Table 74. Reflection of the method implementation process of Phase 4

Port	**Phase 4: Resilience Intervention Analysis**	
	Method Implementation	**Reflection on Applicability**
Pantoloan Port	• Secondary data obtained through desk study is very complete. Analysis was conducted based on resilience staging on the resilience curve results in phase 2.	• The method can be implemented directly because secondary data describing port interventions in the four phases of resilience (preparation, response, recovery, and adaptation) was available in various publicly available sources (official documents, press articles, and port recovery plans). These sources have been verified by the official authorities and the combination of these data can be used directly to conduct phase 4 analysis.
Seba Port	• Secondary data was obtained through desk study. Primary data was obtained through expert interviews to complete the missing information. Analysis was carried out based on resilience staging based on the resilience curve in phase 2.	• This method can be applied directly to the analysis of resilience intervention in the response, recovery, and adaptation phases. This is possible because there are many press articles and official documents through the Ministry of Transportation that explain stakeholder interventions to restore the performance of Seba Port. The analysis encountered difficulties in the preparation phase, which requires primary data from relevant stakeholders to obtain a more accurate picture of the intervention. Permission to conduct interviews with stakeholders can take 3–6 months to obtain.
Mamuju Port	• Secondary data obtained through desk study is complete for post-incident. No data was obtained to explain pre-incident intervention. Analysis was carried out based on resilience staging on the results of the resilience curve in phase 2.	• The application of the phase 4 at Mamuju Port is similar to what happened at Seba Port. There were difficulties in finding primary data to find out what interventions were made by Mamuju Port stakeholders during the preparation period. In the end the analysis can only be done partially (post-incident) and cannot be applied to pre-incident resilience intervention analysis.

7.3 Reflection on the Method's Potential Usefulness for Policymakers and Port Operators

The method developed in this study can contribute to improving the resilience of ports in archipelagic countries to natural disasters by learning from past experiences. This method structures and operationalizes the concept of resilience from scientific theory for practical use in evaluating the resilience of ports in an archipelago. However, it is essential to note that the existence of an effective method will be wasted if the actors who influence enhancing port resilience are reluctant to adopt and use the proposed method in this study.

Policymakers and port operators are the first layer actors that greatly influence port resilience (UNCTAD, 2022). The role of policymakers here is increasingly relevant for archipelagic contexts such as in Indonesia, where most ports (especially ports that have not yet generated economic profits) are supervised and managed by the government. Based on the method implementation, the researcher found that evaluating and improving the resilience of ports in Indonesia is highly dependent on multi-actor agreements or compromises, whether from the Ministry of Transportation, local governments, or port managers. Therefore, an evaluation method that can guide policy analysis activity in a structured manner is not enough; instead, the evaluation method must encourage multi-actors to be willing to use this method and work together to evaluate and improve the resilience of ports in the archipelago.

The way to evaluate it is to take the point that this proposed method is an effective tool to achieve the objectives of the port actors involved by providing the required information (Thissen and Twaalfhoven, 2001). One of the essential reflections to evaluate this method is to look at the results produced by the method and see the potential usefulness of this method based on results produced. To answer this question, we can start by reflecting on the results of this method and relate them to the objectives of the actors to see the method's potential usefulness for policymakers and port operators.

a. *Did the analysis result relate to policymaker's substantive concerns and spheres of responsibility*?

As researchers who developed the method and applied it to three different types of ports, we found four potential uses for this method in policymaking because it produces results related to policymakers' concerns in improving port resilience. The phases that we find useful (without limiting the usefulness of other phases) are phases 3 and 4, the analysis of which is at the port network level. The implementation of phases 3 and 4 can inform the situation and conditions at the network level, which are generally within the responsibility of policymakers to improve its resilience. Based on personal reflection after testing this method on three different case studies, the potential usefulness for policymakers is: (1) Inform resilience planning, (2) Prioritize investment, (3) Standardize Evaluations, and (4) Assessing socio-economic impacts. The following are reflections on each of these potential uses.

The first potential usefulness of the method is that it is capable of informing resilience planning. One of the things that makes resilience planning difficult from a long-term policy maker's point of view is the uncertainty regarding the direct impact of the resilience planning. Applying this method can help policy makers to make resilience planning that is more measurable and based on empirical data. For example, the results of phase 3 analysis in the Pantoloan Port case study related to port-hinterland show that even though there is more than one road connecting Pantoloan Port with other Container Ports, these roads are impassable due to landslides and some have road cracks. The results can provide empirical information that serves as a basis for policy makers to plan for the addition of roads, not only to increase the redundancy in order to improve resilience, but also to build roads in places with a lower risk of landslides.

The second usefulness for policy makers is that this method can help prioritize resilience investments in the midst of limited development budgets. One of the usefulness of this method is its ability to provide justification for upgrading port infrastructure so that an area can be more resilient. This is exemplified by the results of the implementation of phase 3 (port shipping connectivity analysis) in the Seba port case study. The results of the analysis show that when Seba port was closed due to the impact of tropical cyclone Seroja, empirically ships responded by skipping Seba Port or rerouting to Biu Port as an alternative port on Sabu Raijua Island. The results of the analysis show that Biu Port has a reserve capacity of only 20% of the total loading and unloading needs of Seba Port. In addition, Biu Port is shallow in depth so that large ships cannot dock. The small capacity of Biu Port coupled with shallow waters makes many ships choose to skip and anchor at ports on other islands. The results of this analysis can be an important justification for investing in increasing the capacity of Biu Port or building a new port as an alternative on Sabu Raijua Island.

The third potential usefulness for policy makers is that this method can help standardize the process of evaluating resilience in ports, which can later simplify the comparison process and facilitate the policy coordination process. For example, the implementation of phase 2 (resilience curve analysis) offers clear indicators in measuring resilience and its attributes. This analysis can be a standardized and objective benchmarking tool across ports in assessing port resilience. Standardizing this evaluation also allows ports to be ranked based on their past resilience performance. In addition, the implementation of phase 4 (resilience intervention analysis) can be a tool for conducting audits or certifications in distinguishing which ports have considered the aspect of resilience and which have not. In addition to certification, the implementation of phase 4 is also useful for policy makers to audit the conformity of actions with applicable laws, or conversely, it can be input for revising laws that may be too rigid and not in favor of developing port resilience.

The last potential usefulness for policy makers is that this method can help assess the social and economic impact on the community of port closures caused by earthquakes. Take, for example, the results of applying this method to Mamuju port. The phase 2 analysis found that Mamuju Port could not be operated for 370 days due to the Majene earthquake. This result can be the first step to conduct a follow-up study related to how the impact on employment for the local community will change due to the closure of this port. With this output, policymakers can determine a strategy on how to prepare a safety net for the community whose livelihoods depend on port operations.

b. *Did the analysis result relate to port operator's substantive concerns and spheres of responsibility*?

Unlike policy makers, port operators focus on day-to-day efficiency in port operations to achieve competitiveness. After developing, applying, and reflecting on the implementation of this resilience evaluation method, we assess that there are three potential uses of this method for port operators. These three potential uses are explained as follows.

The first potential use for port operators is that this method can help to map vulnerabilities and which infrastructure components are critical in supporting port operations. For example, the application of socio-technical analysis in phase 1 (pre-disaster) and phase 3 (post-disaster) can provide insight into which operational support infrastructure components are most prone to failure against certain natural disasters. For example, the implementation of phase 3 at Pantoloan Port shown in Figure 32 provides insight that Pantoloan port operations are completely paralyzed in both quay and stacking yard operations. The quay operations were paralyzed due to the collapse of the container crane and the damaged container ship dock. In addition, all the social components that support operations were also affected by the earthquake. With this method, the Pantoloan port operator can map out which critical parts require special handling in the future. For example, whether to use a fixed or mobile quay crane.

The second potential usefulness for port operators is that this method can help to carry out risk and resilience performance monitoring on a regular basis, especially in archipelagic regions that are prone to multiple natural disasters. This method is very useful for archipelagic countries like Indonesia, whose territory has the risk of multiple disasters, ranging from earthquakes, tsunamis, volcanic eruptions, floods, tropical cyclones, and other natural disasters. The application of phases 2 and 3 to the three case study ports, for example, can provide insight into the resilience performance of ports for certain disasters, such as earthquakes and tsunamis for Pantoloan Port, tropical cyclones for Seba Port, and earthquakes for Mamuju Port. This method has potential usefulness for monitoring port resilience performance for different types of disasters, so that later on it can be seen what the impact is on the components in the port and how resilience performance shifts to different disasters so that port operators can make business decisions that are more adaptive to different types of disasters.

The third potential usefulness for port operators is to benchmark performance against industry standards. With the use of this method in various ports, it has the potential to help develop industry or best practice standards for port resilience. The results of the implementation of phases 2 and 4 can provide insight for conducting internal benchmarking to ascertain whether resilience performance improves or deteriorates over time. This method also has the potential to be useful for external benchmarking, where ports can make comparisons with other similar ports on a national and global scale. The usefulness of this method for benchmarking can later become data-driven evidence for port operators in determining Key Performance Indicators (KPIs) and Service Level Agreement (SLAs) so that they can track progress towards resilience performance according to industry standards or best practice standards.

7.4 Method's Generalizability to Comparable Ports in the Case Studies

This section analyzes whether the proposed method can be generalized to be applied to ports in Indonesia similar to the ones in the case studies. Indonesia has 3,224 ports as an archipelago. These ports have various characteristics because they were built for different purposes. Of the 3,224 ports, 81% have attributes that are similar to one or more of the three case studies conducted. The remaining 19% are ports with specialized functions, such as fishing, or that specifically distribute oil and gas. In addition, there are eight ports function as main ports or hubs in Indonesia with a much larger service capacity than the ports in the case studies. They have also become Indonesia's trade gateway to the international world. In this section, the discussion will focus on whether this method can indeed be generalized and applied to 81% of the Indonesian ports (around 2,612 ports).

Based on the research and reflection results discussed earlier, the main obstacle in implementing this method (phases 1 to 4) is not in applying the method but in finding high-quality input data to implement the method. The more complete and publicly accessible the available data is , the faster, easier, and more accurate the method can be applied. This is reflected in the Pantoloan Port case study, which was at the center of national attention due to the scale of the disaster and the magnitude of the impacts resulting from the 2018 earthquake and tsunami in Central Sulawesi. Amid Pantoloan port's pivotal position as a container entry point in the Central Sulawesi region, much data from official agencies was released to the public regarding Pantoloan port, both before and after the disaster. This allows the application of the method to be easy and accurate.

Meanwhile, for Seba and Mamuju Ports, the challenge in applying this method was accessing the data needed for the analysis. In some cases, the required data did not exist or needed to be well documented, so extracting it from primary sources through focus group discussions or interviews was necessary. Although it took quite a long time, the data needed was sufficient, and the method could eventually be applied to Seba Port and Mamuju Port. Thus, we conclude that our proposed method, from phase one to phase four, can be used and generalized to ports with similar characteristics to the case study as long as complete and accurate data is available. The more complicated it is to access the data publicly, the more complex or time-consuming it will be when applying this method, especially for independent researchers outside the relevant government or port management organizational structure. This research is also a note to raise awareness for relevant stakeholders in Indonesia to start improving the ease of open access to data needed to apply the phase 1 to phase 4 method, especially for non-containerized and ferry ports, which represent 81% of ports in Indonesia.

7.5 Method's Generalizability to Ports Beyond the Case Studies

This section will discuss the generalizability of this method to ports with characteristics beyond the three case studies presented in this research. The discussion in this section will address the generalizability to ports with different characteristics found in archipelagic countries and ports that are not within archipelagic countries. About 19% of ports with special functions in Indonesia differ from the ports analyzed in this research case study. Take, for example, the fishing port, one of Indonesia's most common ports. The biggest challenge with these specialized ports is that they are generally managed directly by private entrepreneurs with government oversight. In addition, these specialized ports are usually small and have yet to be integrated with modern port information systems. So, the implication for ports in Indonesia is that the data needed to apply this method is rarely publicly available because it does not exist. If the data exists, then the data is labeled as highly confidential.

In addition, port business processes of specialized ports are very different from those of cargo and passenger ports, so implementing our methods at other types of ports must be adapted to the specifics of these ports. For example, the operation of fishing ports in Indonesia depends not only on the port's internal operational process but also on the cooperation between the fishing port and the fish supply chain on the island. In this case, the analysis method in Phase 1 can be adapted. For instance, the social and technical components that need to be considered are the internal and external components of the fishing port. So, we conclude that the generalizability of the method presented in this thesis can work for ports with special functions, provided that the data needed to implement the method is available and accurate, and that the proposed method have been adapted to how the special port operates. This also applies to specialized ports in non-island countries.

For the main ports in Indonesia that also serve international shipping, there are no significant differences in operations from the three case studies conducted in this research. The main differences are that the scale of these ports is generally massive, and the operational complexity is much higher. However, these large ports also typically have more complete operational data because they have more modern information systems than small ports, so the datasets needed to implement this method are much easier to search and find. To deal with the high level of complexity in performing the analysis, we suggest applying the method in a modular manner so that it can be implemented in ports with a larger scale. This has already been exemplified in the application of the method to the Pantoloan Port. Pantoloan Port had three berths, for passengers, general cargo, and containers. In implementing the method, the analysis only focused modularly on the berth handling containers, which was also the most severely affected berth. Therefore, the method can be applied for ports with a larger scale, especially due to the availability of more and more accurate data. This is also particularly true for large-scale ports located in non-island countries.

For generalizations to ports in other archipelagic countries, such as the Philippines or Greece, for ports with similar characteristics, it is possible to follow directly what we did. The quality of the output of the method will depend on the quality of the obtained data. The better the quality of the data, the better the quality of the output. For this reason, other archipelagic countries with a port structure[28] similar to Indonesia can also use the discussion in this chapter to suggest what data needs to be prepared or made available so that port resilience assessment and learning can be directly applied. This study also suggests including the analysis methods of phases 1 and 3 because it is essential to include the archipelagic context in conducting port resilience analysis.

For ports similar to the ports in the case study but in non-island countries, this method can be applied as long as the data required for the analysis is available and accurate. Implementing the method for non-island countries can be done directly at each port using the phase 2 and phase 4 methods without including the spatial context. Phases 2 and 4 are the most critical phases for analyzing individual port resilience in general. This is because Phase 2 can directly measure resilience performance regardless of the specific characteristics of the port. While Phase 4 explains how the decisions made relate to the port's resilience performance for lessons learned. However, Phase 1 and Phase 3 can be applied as well if, indeed, the port resilience analysis is to be carried out by considering the spatial context of the port location so that it can later be known to what extent the disruption of a port in a region will affect the resilience of the region in receiving the flow of containers, goods, or passengers.

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[28] The similarity of the port structure is the similarity of the socio-technical components and the relationship between these components.

8 Conclusions

The preceding chapters of this dissertation examined ways to empirically evaluate port resilience in the Indonesian archipelago using a scientific and practical method. This chapter concludes the contributions and insights gained from this research by answering the research questions. It also states limitations and areas for future research.

8.1 Answers to the research questions

One of the underexplored research studies in port infrastructure, especially in archipelagic countries like Indonesia, is implementing resilience theory into practice for strengthening maritime infrastructure resilience by stakeholders. This is particularly important as most archipelago countries are prone to natural disasters. Previously published research has drawn attention to the emerging need to review and evaluate how resilient ports are in the face of natural disasters and what lessons other ports can learn from these reviews. There was no scientific and practical method to evaluate this at the time of this research. These findings are based on the the literature review in which have been described in section 1.1. Thus, the main goal of this project is to support stakeholders in evaluating port resilience to natural disasters in a practical way. The evaluation results can bring insights into stories of success and failure, both of which are useful to improve port resilience in the future. To achieve this goal, this research was guided by the following main research question:

"How can port resilience to natural disasters in an archipelago be evaluated?"

The main research question has been addressed through the design, implementation, and reflection of a scientific and practical method to evaluate port resilience to natural disasters in an archipelago. To answer this question, the answers to the sub-questions that have been defined are explained sequentially in this section. After answering the sub-questions, at the end of the section it will return to answer the main research question.

8.1.1 RQ1: What key theoretical foundations can be adapted to evaluate port resilience to natural disasters?

Based on the literature review conducted in Chapter 2, it can be concluded that resilience is a concept developed from various scientific perspectives. This causes resilience to be viewed from multiple viewpoints that affect how resilience is defined and operationalized. A systematic literature review is used to find how resilience is conceptualized and applied in the port context. Based on the literature review, three foundations can be adapted for evaluating port resilience to natural disasters to make it more consistent: the definition, operationalization, and conditional resilience. The consolidation of these foundations is described and concluded in Section 2.1 as the basis for evaluating port resilience in this study. The summary of each foundation is explained as follows.

Before evaluating port resilience, it is crucial to answer the question of what port resilience is. The challenge is that the definition of port resilience is being debated in the literature, as shown in Table 2. This leads to unclarity in operationalizing the concept of resilience for post-disaster evaluation purposes.

Based on the literature review described in Section 2.1.1, it is concluded that there are three mainstream perspectives in defining port resilience: Resilience as the capability to withstand disruptions, resilience as the capability to react to disruptions, and resilience as the capability of time to recover. This research combines these three perspectives and defines port resilience as follows,

"Port resilience refers to the engineered ability of a port infrastructure to withstand disruptive shocks, promptly act in response, and quickly initiate and carry out recovery strategies to reinstate acceptable performance following a disruption."

Technically, the choice of words for the definition will always be open to debate. But more importantly, The above definition points out that a resilient port is capable of (1) withstanding shocks, (2) promptly responding, and (3) quickly recovering from disruptions, which is a unification of the three perspectives of resilience in literature. A definition combining these three perspectives was adopted in this study as the basis for evaluating port resilience to natural disasters.

The operationalization of resilience uses the resilience curve, that describes changes in port performance over time (Section 2.1.2). Using this curve as a conceptualization tool, the capabilities required by a port become more consistent so that it can facilitate the implementation of resilience evaluation in real-world ports.

The first resilience operationalization obtained using the resilience curve is to identify the time phases that mark significant changes in port performance. One resilience cycle has four phases: preparation, response, recovery, and adaptation as shown in Figure 4. The second operationalization of resilience clarifies the attributes that represent the three fundamental perspectives in the definition of port resilience.

In order to operationalize the capability of withstanding shocks perspective, the attributes of robustness and vulnerability are used. The attribute for the capability to promptly respond is responsiveness. Likewise, the other attributes that are used to operationalize the capability to quickly recover are recoverability and rapidity. Each definition and calculation formula is explained through changes in port performance over time on the resilience curve as shown in Figure 5. This operationalization using the resilience curve is important in evaluating port resilience in a more consistent way for the entire study.

The third foundation used as a basis for evaluating port resilience is conditional resilience. Conditional resilience is defined as possible outcomes of active effort made continuously to improve the resilience performance of a system. In other words, conditional resilience is about the result comes from conscious decision-making to strengthen port resilience (MCEER, 2005; McDaniels et al., 2008).

There is a method to classify the interventions carried out in achieving conditional resilience. First, from the time of decision-making, it is divided into two, namely *ex-ante mitigation* (taken place before a disruption or natural disaster) and *ex-post adaptation* (interventions taken after a natural disaster). Resilience interventions can be made before or after a disaster. Some pre-disaster interventions perpendicularly affect how a port performs post-disaster. The second categorization of resilience interventions is decision-making based on strengthening the physical infrastructure (*infrastructure-focused*) or the operational processes at the port (*process-focused*).

By combining the categorization based on the timing of decision-making and the focus of intervention, there are four categories of interventions: *infrastructure* and *process preparedness* under the *ex-ante mitigation* category and *infrastructure* and *process adaptation* under the *ex-post adaptation category.* The conditional resilience result from these interventions is shown in Figure 6. These four categories are then used to analyze the interventions made by port stakeholders in evaluating port resilience in a more consistent way. Later, it can be known what interventions are and are not effective as lessons learned in enhancing port resilience.

8.1.2 RQ2: How do the characteristics of ports in the archipelago affect the evaluation of resilience?

In general, the cooperation between components determines the effectiveness and efficiency of a port operation, be it an archipelago port or a non-archipelago port. In understanding how operational performance at the port is formed, one of the efforts that can be done from a systems engineering perspective is understanding what components are in it and how they interact. From the Section 2.3.1, we concluded that social and technical components are two main components that shape a port’s operational performance. These two components and their interaction are the defining components of port performance as shown in Figure 8. Thus, socio-technical system perspective is adopted to analyze the components that shape a port's operations and resilience performance.

Using the socio-technical system perspective implies that the technical and social dimensions are equally important in evaluating port resilience. Existing research primarily concerns technical components without providing a balanced proportion in analyzing the social components. The port is unique as a socio-technical system compared to other systems in general. Technically, ports will have unique operations based on the type of port. Socially, each port has a different hierarchy structure and field operators. Therefore, we conclude that adopting a socio-technical perspective in evaluating port resilience is mandatory for archipelago and non-archipelago ports.

What about the characteristics of ports in archipelagos? The first thing to understand is that archipelagos (especially large-scale archipelagos, such as Indonesia) have complex inter-island interactions. This makes the archipelago an extensive, complex spatial network where islands are connected. This interconnectedness between islands is driven by efforts of communities to fulfill economic supply and demand between the islands. In the perspective of island studies, this concept is known as islands' relationality. In the large-scale archipelago, there are three types of islands' relationality from three categories of islands based on their economic progress and infrastructure. The first is the mainland, the country's economy and government center. Second is the main island, which generally has the potential to be an economic center due to the availability of abundant resources. The third is the periphery islands, which are small in the outer region and usually have limited financial resources. These three categories of islands form islands' relationality in the form of mainland-main islands, main island-periphery islands, and mainland-periphery islands in meeting the needs of goods or the movement of people between the islands.

By adopting this islands' relationality view, ports in the archipelago are built as interfaces and enablers of these relationships. Thus, port resilience is seen from the port's performance and whether the islands' relationality is disrupted. Considering this characteristic, the relationship between ports is cooperative rather than competitive. What cooperative means is that if one port is disrupted on an island, for example, the alternative port provides replacement capacity to maintain the islands' connectivity, not to take market share from other ports. Explanation in Section 2.2 confirms that in archipelagic countries, most ports are not set up as commercial ports but to serve the public so that the islands' relationship can be maintained. This specific characteristic of ports in the archipelago certainly affects how to evaluate ports resilience, where ports are seen not as an isolated entity that operates alone but also as ports that have a role as a component of a complex spatial network and enabler of islands' relationality as shown in Figure 7.

8.1.3 RQ3: How can these theories of resilience and archipelago characteristics be framed and operationalized into a practical method for evaluating port resilience in an archipelago?

Given the need for a method to evaluate port resilience amid fragmented resilience concepts and considering the uniqueness of ports in the archipelago, Section 2.4 focuses on developing a method that can be used in an applicable manner to evaluate port resilience to natural disasters. To develop this method, we use the theoretical framework XLRM (Lempert, 2003; 2019) to evaluate port resilience in a structured manner. XLRM is used to facilitate the complexity of a system and make it easier to understand when conducting a comprehensive system analysis. XLRM stands for four main components in system analysis, namely exogenous uncertainties (X), policy levers (L), relationships (R), and measures of performance (M).

Chapter 3 explains in more detail how the theoretical framework consisting of XLRM components is translated into practical methods based on the formal guidance by McMeekin et al. (2020). The method for conducting port evaluation is divided into four phases of system analysis that is derived directly from the four XLRM components. The first phase is port-system analysis, derived from system relationship (R) analysis. The second phase, resilience curve analysis, is derived from measures of performance (M) analysis. The third phase, disaster impact analysis, is derived from the impact analysis of exogenous uncertainties (X) to system relationship (R), and the fourth phase, resilience intervention analysis, is derived from policy levers (L). Figure 11 shows in more detail the four phases of the practical evaluation method used in this study.

The four phases of port resilience evaluation are designed to assist port stakeholders in understanding port resilience comprehensively so that they can learn lessons to strengthen port resilience in the future. In phase 1 (section 3.2.1), the port as a socio-technical system and its role as a port in the archipelago were analyzed. The expected output of this phase is an understanding of the port as a socio-technical system and its role in the archipelago network as an enabler of islands' relationalities. Block diagrams (Figure 12) are tools to map the port as a socio-technical system. complex network analysis is used to identify the port's role in the archipelago's complex spatial network and the condition of the hinterland and sea transportation networks connected to the port.

In phase 2 (section 3.2.2), this research analyzes how the port performs before and after natural disasters disrupting port performance. Conceptualization and operationalization using the resilience curve are the primary tools in this phase. The expected output of phase 2 is the capture of port performance in a complete resilience cycle, starting from before the port performance is affected by a natural disaster until the performance returns to acceptable threshold. Table 3 shows the calculation formula for resilience attributes in one resilience cycle. Mapping port performance using this resilience curve serves two purposes. First, the level of port resilience can be determined by understanding the resilience attributes that occur throughout one resilience cycle. Second, as a basis for conducting deeper analysis for the next phase to answer why the resilience curve is shaped the way it is. This phase is particularly relevant to demonstrate how port resilience evaluation can be done consistently despite the many fragmented definitions and understandings of the concept of port resilience.

In phase 3 (section 3.2.3), a disruption (in this context, natural disaster) impact analysis is conducted. The analysis in this phase is facilitated by a block diagram and complex network analysis to mapping the condition of the port’s socio-technical components and the islands' relationalities immediately after the disaster. The expected output of phase 3 describes which social and technical components were affected by the disaster, where the Port Infrastructure Damage Assessment (PIDA) sheet was used to assess the impact on the components as shown in Figure 13. After the assessment using PIDA, the block diagram was used again to visually depict the affected port components and their severity. In addition, changes in islands' relationality were also mapped after the disaster, including changes in transportation networks on the sea and land sides. The analysis results at this phase can explain further the level of port's robustness or vulnerability on the resilience curve. Hopefully, ports with similar characteristics can expect and learn about the impact of a specific natural disaster on the port.

In phase 4 (section 3.2.4), a more in-depth analysis was carried out related to the resilience intervention by port stakeholders. This resilience intervention analysis used secondary documents and primary data from stakeholder interviews. The data collected was then classified into four categories of resilience intervention. The purpose of phase 4 is to study what interventions are taken to improve resilience and how they impact port performance after natural disasters. It is expected that the results of phase 4 analysis will assess what interventions are effective and ineffective in increasing port resilience in the archipelago, as seen from the resilience curve produced in phase 2. The analysis results of these four phases are then synthesized into lessons learned that can be used to improve port resilience in the future.

8.1.4 RQ4: How can the proposed method be applied to different types of ports in the archipelago to evaluate their resilience?

Three case studies were selected for port resilience evaluation to determine the extent of application of the port resilience evaluation method designed in this research. These three case studies were taken from three disaster events that significantly impacted ports in Indonesia. They were also selected based on the different characteristics of the affected ports and the types of natural disasters that occurred. Chapters 4 to 6 of this thesis presented the application of the method, results, and insights from each phase of the port resilience method. The following sections present the conclusions of the port resilience method implementation for each case study.

A. How does the proposed method help evaluate Pantoloan Port's resilience to Earthquake and Tsunami?

Pantoloan Port is a commercial port that is one of the significant and central ports in Central Sulawesi Province. The port serves multipurpose vessels, but the container terminal was the most affected during the earthquake and tsunami in Central Sulawesi in 2018. In the implementation of phase 1, adjustments were made to the socio-technical analysis procedure by focusing only on container operations carried out at a specialized container loading and unloading berth. During the implementation of phase 1, no significant obstacles were encountered due to the availability of a required data to do the analysis was sufficient.

Phase 1 helps understand the context in which the characteristics of the port system are being analyzed. Data obtained from official documents and the transcript of stakeholder interviews became the reference for thoroughly describing Pantoloan Port's socio-technical components. Interactions between socio-technical components that form the port operations are mapped using block diagrams. Meanwhile, data on the relationship of Pantoloan Port with the hinterland road network and shipping connectivity in the region was obtained through government documents, which are relatively complete and supported by AIS data to describe the situation of islands' relationalities accurately. Complex network analysis using QGIS and Python is used to analyze the data. Implementation in phase 1 found no significant obstacles in the data gathering and analysis process.

Phase 2 focuses on describing port performance in one resilience cycle. The metric used in this measurement is Container Vessel Capacity (CVC). The performance measured in this study is the port's productivity in receiving and discharging container ships. CVC only calculates the maximum theoretical capacity of ships that dock or sail from a port. The resilience curve is created using data from AIS and INAPORTNET, a port information system in Indonesia, to describe the resilience curve accurately. In the implementation of phase 2 at Pantoloan Port, no significant obstacles were found, and the method can be implemented well.

Phase 3 described the impacts of natural disasters that disrupted the port. The impacts identified include the effects of natural disasters on socio-technical components and how islands' relationalities change due to the disruption of Pantoloan port operations. Similar to the data used in Phase 1, official data, interviews, and field visit reports were used to assess how the earthquake and tsunami natural disasters impacted the socio-technical components of Pantoloan Port. The Port Infrastructure Damage Assessment (PIDA) was developed in this study, and the block diagram was used as the primary tool to map the affected socio-technical components. To map changes in islands' relationalities, data from the Ministry of PUPR was used as input to conduct complex network analysis to show how changes in hinterland connectivity and data from AIS were reused to determine changes in connectivity on the seaside. In general, the implementation of phase 3 at Pantoloan Port was smooth because the required data were available and complete.

Phase 4 focused on analyzing the interventions taken by port stakeholders to improve port resilience. Most of the data used was secondary in the form of official reports, field surveys, and articles from mass media. These data were then classified based on the time of decision-making by the time division in the resilience curve created in phase 2 and based on the level of decision (whether at the port level or network level that can strengthen the resilience of islands' relationalities). The implementation of phase 4 at Pantoloan Port was smooth because the required data was fully available. The results of these four phases of analysis can then help draw lessons as to why resilience performance at Pantoloan Port is the way it is by investigating the interrelationships pattern between the port context, resilience performance, the impact of natural disasters, and the interventions taken by port stakeholders in dealing with disruptive events.

B. How does the proposed method help evaluate Seba Port's resilience to Tropical Cyclones?

Seba Port on Sabu Island is one of two ports that serve as an entry and exit point for passengers and goods on Sabu Island. Seba Port is non-commercial, meaning it was built and managed by the government to provide public services to residents of remote and outer islands. Seba Port serves general loading and unloading of cargo as well as loading and unloading of passengers. However, in this case study, the resilience evaluation is focused on the port's performance in serving the loading and unloading of freight vessels because it is the most affected service due to the tropical cyclone Seroja incident that occurred on April 3-12, 2021.

In phase 1 implementation, the socio-technical components of Seba Port were analyzed from secondary data from official documents and interviews with port stakeholders. Then, the socio-technical components of Seba Port were depicted in the form of a Block Diagram. For analysis related to the role of Seba Port on islands' relationalities, no obstacles were found for the relationship between Seba Port and the hinterland road network because the available data were complete from the central and local government. Meanwhile, the analysis of the role of Seba Port as an enabler of inter-island shipping connectivities has data constraints. Seba Port is not covered by AIS and INAPORTNET services due to its position as a small and outermost port in Indonesia, so the complex network analysis related to the seaside needs to be improved.

To solve this, this study uses similar data from the official government system, SIMLALA. SIMLALA registers vessel operation plans (VOPs), which contain a list of routes for vessel voyages approved by the government. SIMLALA provides an alternative to conduct phase 1 analysis and implementation more quickly but is subject to biased accuracy as vessel operating plans often do not match on-the-ground implementation. Another alternative that can be used is to contact the port operator directly through interviews or requests for documents recording ship arrivals (port calls) at Seba Port. However, based on experience in this study, procedures to get permission for obtaining this data are complicated and time-consuming. The advantage of using primary data is that the port shipping connectivity analysis results can be more accurate than those of using data in SIMLALA.

In phase 2 implementation, there are adjustments to the performance metrics measured from Seba port. This research uses the Cargo Vessel Capacity (CVC_{Cargo}) metric as the port performance mapped with the resilience curve. CVC_{Cargo} chosen because Seba Port does not serve container ships, only general cargo ships, for loading and unloading goods. CVC_{Cargo} shows the maximum theoretical capacity of ships served at Seba Port. Data from SIMLALA can be used to create the resilience curve, assuming that the approved vessel operation plan is no different from the actual implementation. However, using SIMLALA can be a risky bias, especially on ship routes after the disruption of Seba Port. For this reason, this study uses internal port call data from Seba Port, which is not publicly accessible. As an implication, the implementation process in phase 2 is quite time-consuming due to data limitations and the lengthy bureaucracy or permission required to access data to create a resilience curve.

In the implementation of phase 3, there were no process adjustments, and this study still used the same implementation process as the other ports. The impact of damage caused by natural disasters on the socio-technical components of the port was assessed using a PIDA sheet and visually represented in the form of a block diagram. The secondary data used as the basis of the analysis is from mass media articles because, at that time, the Seroja tropical cyclone disaster received enough attention nationally. The limitation of data issued from official governments and organizations made this study experience difficulties in cross-checking data accuracy from mass media. This research ultimately explored internal data obtained from port operators and the Ministry of Transportation as the port authority. The implication is that the implementation of phase 3 took a long time because it required various permissions and went through time-consuming bureaucratic procedures. However, the availability of extensive mass media coverage gives this study an alternative if the stakeholders want to do the analysis more quickly.

In the implementation of phase 4, there are no adjustments, and the analysis process still uses similar procedures in general. The data is mostly from mass media coverage related to how interventions are carried out in the resilience cycle range. Additional data related to the intervention is obtained from internal data after obtaining permission from the Ministry of Transportation, which can be opened as a form of public service for scientific research and dissemination.

C. How does the proposed method help evaluate Mamuju Port's resilience to Earthquake?

Mamuju Simboro Port in West Sulawesi was chosen as the third case study representing the passenger crossing port affected by the Mamuju Earthquake on January 15, 2021. The port is commercially managed by PT ASDP Indonesia Ferry to strengthen the inter-island maritime connectivity, especially between West Sulawesi Province and East Kalimantan Province. This case study focuses on measuring the port's performance in serving passenger crossings, which differs from the previous two ports.

In phase 1 implementation, analyzing the socio-technical components of Mamuju Port took a long time due to the unavailability of publicly available and accessible secondary data. The socio-technical component analysis could only be carried out after obtaining access and permission from the central government through the Ministry of Transportation. As for the analysis of Mamuju Port in its role in maintaining inter-island connectivity and island relationalities, no problems were found in conducting port-hinterland connectivity analysis between Mamuju Port and other alternative passenger ports on Sulawesi Island, which also serves crossings to East Kalimantan.

Data from the central government regarding the port-hinterland network topology can be obtained entirely and openly through official data from the Ministry of Public Works and Housing. Another difficulty is conducting port shipping connectivity analysis with ports outside Sulawesi Island; publicly accessible data also constrain this research. The analysis almost could not be done because no data was available. Still, in the end, it got approval through the Ministry of Transportation, which gave PT ASDP Indonesia Ferry a recommendation to open internal data for research purposes.

In the implementation of phase 2, there was an adjustment to the metric used to measure the performance of Mamuju Port. The metric used is Passenger Vessel Capacity (PVC). PVC shows the maximum capacity of vessels that can be served by Mamuju Port both before and after being affected by the Earthquake disaster. Data availability is again a challenge in implementing phase 2. One strategy that can be used to conduct a quick analysis is to extract publicly published departure schedules, such as through Ferrizy's online ticketing platform. Extracting schedules from online ticketing platforms can be an alternative to conducting resilience curve analysis quickly and accurately. However, internal port call data is also used in this study, although accessing it requires an access permit and considerable bureaucracy.

In phase 3, the implementation process did not change, and the procedures were used the same as in the other ports. The earthquake's impact on the socio-technical components of Mamuju Port was assessed using a PIDA sheet and then visually mapped using a Block Diagram. Much of the data used to conduct the socio-technical impact analysis was obtained from articles in the mass media. The coverage of the disaster and its impact on Mamuju Port was quite massive because this port is the critical gateway for passengers in West Sulawesi who want to cross to East Kalimantan and vice versa. Many national and local mass media outlets covered the condition of the port after being affected by the disaster. The availability of this data is beneficial because the data released from government agencies is minimal. Mass media articles are, again, the primary reference for the condition of port-hinterland relations because of the large amount of coverage that also explains the condition of the roads connecting Mamuju port with other alternative ports.

Meanwhile, data from the online ticketing platform was used to map the condition of shipping connectivity between Mamuju Port and other ports in East Kalimantan after Mamuju Port was affected by the earthquake. In this study, requests for data on post-disaster port call changes were attempted to be made to the port operator. Still, the request for the data needs to be responded to, so the only data used was the dataset from the online ticketing platform.

In the implementation of phase 4, there was no change in the resilience intervention analysis procedure. The implementation of phase 4 needed to be improved and almost could not be executed due to the lack of available data and the difficulty of obtaining sources that could be interviewed. The strategy taken to make this phase 4 can be implemented is to collect articles from the mass media during the span before the disaster until the duration of one resilience cycle that has been mapped in the resilience curve made in phase 2.

In conclusion, the resilience evaluation method proposed in this study can be applied to a wide variety of ports by considering two things: the availability of the required data and the implementation process of the method can be adujusted or adapted following the specific characteristics of the port. As long as the required data exists, the process of implementing this method can proceed. The availability of this required data is a prerequisite in applying this method in the real world. The ideal required data needed to implement this method is data that comes from a real-time system with entries that are accurate, complete, verifiable by official sources, and widely accessible to the public.

However, based on the case study in Chapter 4, 5, and 6 of applying the method to different ports, it is concluded that in Indonesia, each different port has a different degree of required data availability for each phase. For commercial container ports, it was found that there is a complete set of primary and secondary data available to conduct the analysis, making resilience evaluation easy. For multi-purpose, small public ports, it was found that the data needed to conduct port shipping connectivity analysis in phases 1 and 3 were the most difficult to find, requiring strict permission to access the required data. Meanwhile, for commercial passenger ports, it was found that it was difficult to find data for almost every phase, except for the data to conduct ports-hinterland connectivity analysis in Phase 1 and Phase 3, which were fully available and publicly accessible.

To overcome this, this research uses other alternative data sources that are publicly available to facilitate replication and reproducibility, such as reports from independent researchers, articles in the mass media, articles in scientific journals and direct contact with stakeholders related to the disaster incident in the case study. Searching for data from these other sources consumes a lot of additional time compared to when the data is already available and can be directly processed with this proposed method.

Another thing that needs to be considered in implementing this method at different ports is to ensure that the method can be adjusted or made adaptable to the specific characteristics of the port. For example, the application to Pantoloan port requires a slight adjustment in the socio-technical analysis procedure of phase 1, i.e. the analysis is made modular focusing only on berths that handle container only. This was done because the Pantoloan Port analyzed has berths with different functions, such as berths for containers, bulk goods, general cargo, and for passengers. In the implementation of phase 1, socio-technical analysis is focused on the container berths because they are the most affected and cannot be replaced with other berths because they require specialized equipment, such as quay cranes.

Another adaptation of the implementation process is to adjust the performance indicators used for the resilience curve analysis conducted in phase 2. For Pantoloan Port which handles containers, the resilience curve was formed by measuring the Container Vessel Capacity (CVC) visiting Pantoloan Port in one resilience cycle. Meanwhile, Seba Port uses Cargo Vessel Capacity (CVC_{Cargo}) and Mamuju Simboro Port uses Passenger Vessel Capacity (PVC). For the implementation process in the other phases, it does not require significant adjustments. This means that as long as the required data is available, the three ports can directly use this method in other phases.

In summary, the methods for evaluating port resilience in three different port case studies only require minor adaptation to be implemented as long as the required data is available. This also shows that the proposed method is flexible and also opens up opportunities to be applied to many ports located in Indonesia with different characteristics.

8.1.5 RQ5: What are the method’s potentials beyond the case studies when applied to comparable or different ports?

This research has examined the method's effectiveness in evaluating port resilience in three case studies. In the three case studies, although the method was applied to three ports with different contexts, all phases could be implemented successfully with minor adjustment to its process, provided that required data that could be used to show past conditions were sufficient, available and publicly accessible. The less or no data is available, the less feasible the application of the method will be.

What is the potential application of this method in other ports with characteristics similar or comparable to those of the ports in the case studies? Based on the observation of the implementation in three case studies with different ports, this method has a high potential for flexibility with only a few adjustments needed in the socio-technical analysis in phase 1 and the performance indicators used for developing resilience curve in phase 2. However, to be able to apply this method, each port analyzed needs to provide the required data. The less required data available and publicly accessible, the more difficult the implementation of this method will be even though the method itself is flexible.

For ports that have specificities and operations that are very different from the ports in the case study, such as fishing ports or oil and gas terminal ports, there is a need to adjust the method itself. This is based on the operational process of ports with significant differences, such as fishery ports. Fishing ports have different operational processes, such as fish being a perishable commodity that requires reefer or refrigeration, and the loading and unloading process and storage at the port are very different from ports of goods and people in general. In archipelago countries such as Indonesia, these fishing ports are generally also integrated with markets and fish auctions. This causes the analysis of socio-technical system components to need to be careful, whether it requires analysis involving the market or only the port.

However, based on the experience of applying this method, the phases that need to be adjusted are phase 1 to analyze the socio-technical system, phase 2 to adjust the indicators in developing the resilience curve, and phase 3 to analyze the impact of disasters on socio-technical system components. For applications in ports that still have operations similar to the case study but have a much larger scale, the method can be used modularly by scoping the operations affected by the disaster and the relevant parts only. For example, if the port has four terminals and only one terminal is affected, then the analysis can be done by focusing only on that terminal.

8.1.6 Main RQ: How can port resilience to natural disasters in an archipelago be evaluated?

After answering all the sub-questions outlined in the previous subsection, it is time to answer the main research question. The main question of this research is, "*How can port resilience to natural disasters in an archipelago be evaluated?*". To answer this, a four-phase resilience evaluation method was derived from a scientific literature synthesis and then tested on ports in an archipelago.

The four phases that have been developed can serve as a checklist in evaluating port resilience performance. These four phases do not need to be used sequentially or all of them, but can be used according to the needs or objectives to be achieved. For example, to quickly evaluate the resilience of a port, regardless of whether the port is in an archipelago or not, phase 2 (resilience curve analysis) can be used without the need to analyze the other phases. Phase 2 is useful to measure what the port's resilience is in one resilience cycle through the resilience curve, starting from the port's performance before the disaster disruption, until the port's performance bounces back to the minimum acceptable performance.

In addition to illustrating the resilience curve in one cycle, the analysis in phase 2 also offers quantitative and qualitative approaches to measure port resilience attributes, including to quantify various resilience attributes in the literature, such as: robustness, vulnerability, responsiveness, rapidity, and recoverability. The adjustments that need to be made are related to the indicator use to measure port performance, because each port may have different key performance indicator.

If stakeholders want to conduct a more in-depth evaluation of port resilience to obtain lessons learned that can be used to make the port better prepared in the future, then phases 1, 2, 3 and 4 can be used. There are two options in using phases 1, 3, and 4, namely whether to see a port as an exclusive, independent entity or to see a port as an entity that is part of a network. The first option that sees the port as an independent entity is generally used by stakeholders who have the view that the port is a commercial business and sees other ports as competitors. For this type of port, stakeholders can utilize phases 1, 3, and 4 at the internal port level only.

For example, the analysis of phases 1 and 3 focuses only on analyzing the socio-technical components of the port, and phase 4 analyzes the interventions carried out only at the scope of internal port system. Adding phases 1, 3, and 4, in addition to conducting phase 2 can be useful to draw important lessons regarding what causes the port's resilience to have that performance and what strategies are effective or ineffective for that particular port in improving resilience.

For stakeholders in the archipelago, the perspective used to measure port performance is the second option that sees the port as a part of the archipelago's complex network. In this second option, ports are seen as a means to improve people's welfare, especially in remote islands. Using this perspective, ports in an archipelago are generally managed by the state, or state-owned enterprises, whose business relationships with other ports are more cooperative than competitive. This cooperative nature is based on the port's interest in working together to maintain the connectivity of the island with ports in other areas. Therefore, the evaluation of resilience in island nations needs to be broader than just looking at the internal system of the port in responding to disasters. Because of its cooperative nature, port resilience in an archipelago needs to be seen whether it is affected by the existence of alternative ports in the vicinity, how hinterland connectivity connects the disrupted port with alternative ports, and how much impact the disrupted port has on the shipping connectivity of the island.

To evaluate port resilience to natural disasters in the archipelago, government, researchers or stakeholders can use an analysis that not only focuses on the internal port, but also changes in the dynamics of shipping connectivity network on the island and the condition of the hinterland between alternative ports on the island. To evaluate and learn lessons at this level, phases 1, 3, and 4 are complemented by quantitative and qualitative approaches given an asterisk (*) in the phase shown in Figure 11. The execution of the process in the phase given an asterisk (*) indicates that the analysis carried out is not only focused on analyzing the port in isolation, but also analyzing how changes in island's transport network connectivity can affect port resilience in an arhcipelago.

The application of this method from phases 1 - 4 including the analysis with asterisk mark concludes that it is important to include an analysis of the port as a component of a more complex network, rather than as an independent entity on an island. The application to Pantoloan Port (Chapter 4) can confirm this conclusion. When Pantoloan Port was affected by the earthquake and tsunami where the quay crane was broken and unable to function, Makassar port was calculated to have enough spare capacity to replace the loading and unloading capacity of Pantoloan port.

However, through the island's shipping connectivity analysis in phase 1 and 3, Makassar Port became a transit place for refugees from Palu and surrounding areas who were victims of the earthquake so that the spare capacity was reduced and difficult to use for loading and unloading containers from ships that originally wanted to load and unload at Pantoloan Port. Meanwhile, through the ports-hinterland network analysis in phase 1 and 3, the result is roads connecting to other alternative ports that have container reserve capacity other than Makassar Port are severely affected and cannot be passed by container trucks. This caused Pantoloan Port to be forced to reopen as quickly as possible even though the quay crane facility had not been repaired. As the result, Pantoloan Port was reopened without a dedicated quay crane and only relied on on-board cranes on anchored ships with a productivity of only 30% of normal conditions, in order to maintain the stability of container flows on Sulawesi Island due to difficulties in utilizing spare capacity at other ports. The return of capacity only occurred when Pantoloan Port successfully transferred mobile quay cranes from Bitung Port in the north of Sulawesi Island because it had more capacity and less container loading and unloading demand. Lessons learned from this evaluation are explained in more detail in Section 4.5.

The above findings show that there is a very close cooperative relationship between one port and another port on an island in enhancing port resilience in an archipelago. Thus, shipping connectivity and port-hinterland network analysis are concluded to play an important role in evaluating port resilience on an island. This conclusion is also confirmed by the findings in the evaluation results at Seba Port and also Mamuju Simboro, where the strength or lack of resilience of the port is influenced by factors of alternative port on the island and the quality of hinterland connectivity that connects alternative ports with disrupted ports. More complete lessons learned can be seen in Section 5.5 and Section 6.5.

Finally, we conclude that the four-phase method in this study can be used to evaluate port resilience to natural disasters in an archipelago. To gain comprehensive lessons learned, we found that it is important to analyze both the internal port and the alternative ports connected to the disrupted port. For ports on an island within an archipelago whose business model is to cooperate with each other, utilizing this method from phase 1 - 4 (including the analysis marked *) can help map the role of alternative ports and hinterland conditions on the resilience of the disrupted port. This role will not be obtained if the analysis marked (*) is not carried out so that it can provide less lessons learned. Therefore, to evaluate port resilience to natural disasters in an archipelago: rather than focusing only on evaluating individual ports, the lessons learned will be more insightful if the evaluation include the role of alternative ports that shaped the island's connectivity.

8.2 Limitations of the research

This research aims to develop an evaluation method for port resilience in the archipelago. The biggest challenge in developing this evaluation method was to unify the conceptual understanding of port resilience in an archipelago before operationalizing it for evaluation. The first limitation of this research lies in the limited literature sources on port resilience in the archipelago context. We found that the majority of the literature on port resilience comes from ports located in non-archipelago regions, such as in the Americas and Western Europe. This literature was then synthesized into a consolidated port resilience concept to be developed into a method for evaluating port resilience in the archipelago. The port resilience literature, the majority of which comes from non-archipelago countries, contains the possibility of not being able to fully cover the concept of port resilience that is relevant to ports in archipelago countries. As a result, the method developed in this research may not be able to cover all the characteristics of ports in the archipelago that need to be considered because the majority of port resilience understanding is taken from non-archipelago literature.

The second limitation of this research is that the case study sampling is limited to one country, namely Indonesia. The method developed in this study has not been tested on special ports in Indonesia, such as special ports for oil and gas, coal, or fishing. In addition, the port evaluation method in this study has also not been tested on ports in archipelagic countries other than Indonesia. Thus, it is too early to conclude if this method can provide the same effectiveness in evaluating ports in archipelagic countries other than Indonesia.

A third limitation of the method's applicability is that it was tested on a limited subset of natural disaster incidents. The selected case studies represent three natural disaster incidents: Earthquake, Tsunami, and Tropical Cyclone. These three natural disasters are Indonesia's most frequently occurring natural disasters. However, there are many other natural disasters that Indonesian ports commonly experience, such as coastal flooding, extreme rainfall or volcanic eruptions. The effectiveness of the evaluation method cannot be concluded for disaster incidents other than those practiced in this case study.

The fourth limitation of this research is the limited engagement with port stakeholders and port visits that can be carried out to test this method directly, so the data in the form of tacit knowledge from relevant stakeholders is very limited to process. One of the main causes is due to the peak of the COVID-19 pandemic whose timeline coincides with the development of this method. The initial research plan was to develop this port resilience evaluation method by conducting intensive communication with stakeholders from the Sea Transportation Research Agency, Ministry of Transportation of the Republic of Indonesia.

However, COVID-19 significantly made the original plan to develop this method unfeasible due to increased bureaucratic complexity. Thus, the strategy was to conduct remote surveys and remote communication on a limited basis. This increase in bureaucratic complexity also forced us to shift our orientation to collect data from explicit knowledge by trying to find secondary data published on government websites and mass media as a substitute for tacit knowledge which is very difficult to obtain. The implication of this research is that there may be some empirical events that were not identified in this research due to the lack of interaction with stakeholders directly, especially those who were key witnesses when the port was affected by the disaster until the port returned to the minimum acceptable performance.

The fifth limitation of this research is the limitation that lies in the knowledge of port stakeholders who are willing to be involved in this research in the implementation of phase 4, namely resilience intervention analysis. The first limitation of stakeholders is that the interviewees are still not familiar with the concept of port resilience. Many stakeholders still confuse port resilience with port risk management or risk response. This is because research on port resilience is still scarce in Indonesia. This has resulted in stakeholders focusing on and remembering disaster preparation strategies, rather than documenting or remembering post-disaster response and how the port has bounced back. The implication for the research is that many resilience intervention points can still be found considering that the stakeholders involved in the research did not document or find it difficult to remember what responses were made especially after weeks or months from the date of the disaster.

Another limitation is that the stakeholders are already different between those who experienced the disaster and those involved in this research. This limitation was especially true in case study 1, where the disaster occurred in 2018. By the time this research was conducted in 2021, the stakeholders handling the port had changed and could not provide detailed information about what happened at the port at that time, potentially leading to inaccurate data. For case studies where the tacit knowledge of stakeholders is less reliable, the focus on finding documents and data in the form of explicit knowledge is prioritized in this research.

8.3 Recommendations for use and research of the method for evaluating port resilience in an archipelago

This research project is a study to pave the way for the port resilience concept to be operationalized and evaluated in archipelago ports affected by natural disasters that have already occurred (*ex-post*). The evaluation method produced in this study is expected to help draw lessons learned that can be used to improve port resilience in Indonesia. This research shows that the method developed to evaluate port resilience in the archipelago is practical. Therefore, this method is recommended for port stakeholders who want to evaluate the port's resilience and gaining lessons that can be learned from the evaluation. The following recommendations will help implementation of this method in the future.

First, applying this method requires extensive data for each phase to be used effectively. Available, complete, and accurate data will significantly assist the application of this method. It is recommended that data platforms such as INAPORTNET developed by the Government of Indonesia through the Ministry of Transportation be applied more widely and thoroughly to various ports in Indonesia to obtain the data needed to utilize this method. The data needed is the complete entry on the socio-technical components of the port, number of ship entries and exits, the number of daily ship loading and unloading volumes, and the recording of important decisions to deal with disasters, both before and after the disaster. In Indonesia, the government has an information system platform that is useful for receiving and storing public port data, which is needed to use this method. However, it still needs to cover all ports in Indonesia. Thus, this study recommends public entities in Indonesia as the primary users of this method in consideration of the data's completeness and easier access to monitoring and port visits if needed.

Secondly, for independent researchers who wish to use this method, the study recommends that each researcher ensure that the data required to implement the method phases are available and sufficient. Chapter 7 discussed in more detail what examples of ideal and alternative data can be used to successfully evaluate port resilience using the method proposed in this study. One way to ensure data availability is to initiate a joint research contract or MOU between the researcher and port stakeholders that require data to implement the method. If this is not possible, then the recommendation from this study is that the government or port stakeholders who own the data should make it easy to access for research purposes. The ease of this procedure can be started by providing clear information about who can be contacted to obtain the data needed in the analysis. In addition, the government can also establish standardized regulations regarding which data can be shared and which cannot be shared with external parties. For general port data that the government cannot provide, the government can provide recommendations through its network regarding other primary sources that can be alternative data and are still relevant to support the successful use of this port resilience evaluation method.

Third, the advantages and disadvantages of this method for evaluating port resilience have been demonstrated through the three case studies conducted. The three case studies representing 80% of the public ports in Indonesia, one of the largest archipelagic countries in the world. Thus, the recommendations given for researching the method in the future can be tried at ports with characteristics other than those demonstrated in the case study. It is intended that the method proposed in this study can be tested for generality or get iterations to be more effectively used in other port contexts. Further research recommendations are for the following ports: (1) ports in Indonesia that have special functions, such as oil and gas ports, mining products, or fishing ports; (2) ports in other archipelagic countries besides Indonesia, such as the Philippines, Japan, or Greece; (3) ports in countries that fall into the Small Island Developing States (SIDS) category, such as Timor Leste, Bahamas, Papua New Guinea, and other SIDS countries.

The last recommendation given is that the results of the analysis from using this method can be collected and compiled into an integrated database that every port stakeholder can access to learn from each other. Each port that has applied this method can take initiative to open and share what the results of the port resilience evaluation to certain natural disasters. That way, each port stakeholder can learn from other ports regarding what strategies are successful and what strategies fail in enhancing resilience. With structured data-sharing from various ports using this method, it is hoped that this method can contribute to fostering collaboration and promote a more coordinated approach among different port stakeholders (government, port operators, local communities) to enhance port resilience.

Future research recommendations could focus on how to make the analysis results from using this method a basis for calculating cost-benefit before deciding what resilience interventions to take. In addition, further research to standardize the result of analysis using this method and how to make it publicly accessible can be followed to accelerate the dissemination of port resilience evaluation results in various ports around the world, especially ports located in archipelagic countries, such as Indonesia.

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About the Author

Arry Rahmawan Destyanto (Arry) was born in Tangerang, Indonesia on December 5th, 1990. He obtained his bachelor's and master's degrees from the Department of Industrial Engineering, Universitas Indonesia (UI). He has research interests in systems engineering, modeling, simulation, and serious games applied in supply chain, transportation, and logistics.

After graduation, he was appointed as a faculty member at his alma mater, the Faculty of Engineering Universitas Indonesia, at the end of 2016. In 2019, he started working as a PhD student in the Policy Analysis Section, Faculty of Technology, Policy, and Management (TPM), funded by the Indonesia Endowment Fund for Education (LPDP, *Lembaga Pengelola Dana Pendidikan*) through the Indonesian Lecturer Excellence Scholarship (BUDI) scheme with project number ID 20193223014052.

In his spare time, Arry enjoys reading self-development books, writing on his blog arryrahmawan.com, and playing computer simulation games to hone his system thinking skills. After completing his PhD, he will return to Indonesia to teach and develop his knowledge and research interest at the Systems Engineering, Modeling, and Simulation (SEMS) laboratory, Department of Industrial Engineering, Universitas Indonesia.

Publications

Destyanto, A. R., Huang, Y., & Verbraeck, A. (2021). Examining the spatiotemporal changing pattern of freight maritime transport networks in Indonesia during COVID-19 outbreaks. *ACM International Conference Proceeding Series*, 590–597. https://doi.org/10.1145/3468013.3468662

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Presentations

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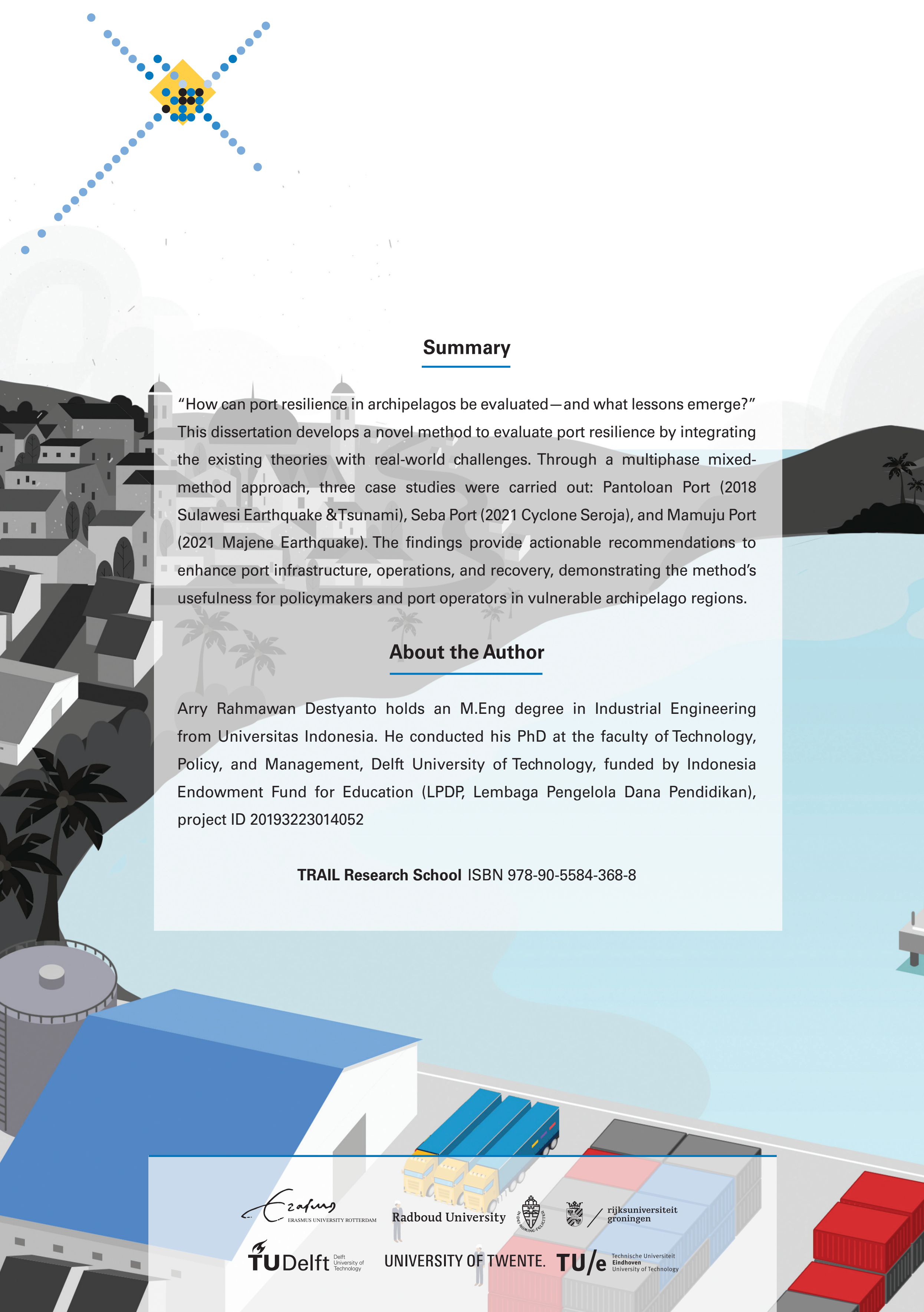

Summary

"How can port resilience in archipelagos be evaluated—and what lessons emerge?" This dissertation develops a novel method to evaluate port resilience by integrating the existing theories with real-world challenges. Through a multiphase mixed-method approach, three case studies were carried out: Pantoloan Port (2018 Sulawesi Earthquake & Tsunami), Seba Port (2021 Cyclone Seroja), and Mamuju Port (2021 Majene Earthquake). The findings provide actionable recommendations to enhance port infrastructure, operations, and recovery, demonstrating the method's usefulness for policymakers and port operators in vulnerable archipelago regions.

About the Author

Arry Rahmawan Destyanto holds an M.Eng degree in Industrial Engineering from Universitas Indonesia. He conducted his PhD at the faculty of Technology, Policy, and Management, Delft University of Technology, funded by Indonesia Endowment Fund for Education (LPDP, Lembaga Pengelola Dana Pendidikan), project ID 20193223014052

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