Journal of Infrastructure, Policy and Development 2024, 8(16), 9284.
https://doi.org/10.24294/jipd9284

Article

The sustainable transportation model in Lake Towuti: Assessment of safety and management with MICMAC analysis

Feronika Sekar Puriningsih[1,2,*], Muhammad Isran Ramli[1], M. Saleh Ali[1], Johny Malisan[3]

[1] Development Study Program, Graduate School, Hasanuddin University, Makassar 90245, Indonesia
[2] Research Center for Transportation Technology, National Research and Innovation Agency (BRIN), Serpong, South Tangerang 15314, Indonesia
[3] Research Centre for Economics of industry, services, and Trade National Research and Innovation Agency (BRIN) South Jakarta, DKI Jakarta 12710, Indonesia
*** Corresponding author:** Feronika Sekar Puriningsih, ferospuriningsekar@gmail.com

CITATION

Puriningsih FS, Ramli MI, Ali MS, Malisan J. (2024). The sustainable transportation model in Lake Towuti: Assessment of safety and management with MICMAC analysis. Journal of Infrastructure, Policy and Development. 8(16): 9284.
https://doi.org/10.24294/jipd9284

ARTICLE INFO

Received: 24 September 2024
Accepted: 18 October 2024
Available online: 25 December 2024

Abstract: This research investigates the safety status of water transport in Lake Towuti, South Sulawesi, employing the MICMAC and MACTOR methodologies to discern the factors that affect navigation safety and the interactions among the relevant stakeholders. The MICMAC analysis reveals that the effectiveness of sustainable transportation in Lake Towuti is significantly dependent on technical elements such as vessel certification, maintenance practices, and safety monitoring, alongside robust relationships among key entities like The South Sulawesi Class II Land Transportation Management Center (BPTD), The East Luwu District Transportation Office (Dishub), and the Timampu Port Service Unit (Satpel). When implementing the MICMAC-MACTOR model, it is essential to consider the technical implications of the proposed recommendations from the perspectives of social justice, environmental sustainability, and economic feasibility. The outcomes derived from the MICMAC and MACTOR assessments in Lake Towuti provide critical insights that can be utilized in other lakes across Indonesia, especially those that exhibit deficiencies in safety measures and adherence to inland water transport safety regulations.

Keywords: safety; IWT; traditional ships; MICMAC; MACTOR

1. Introduction

Water transportation, whether through rivers or lakes in rural areas, plays a crucial role in facilitating community mobility and supporting the local economy, particularly in regions with limited access to land-based infrastructure (Jurkovic et al., 2021). Inland water transportation encounters numerous obstacles, including issues related to governance, inefficiencies in management, operational challenges, inadequate infrastructure, and a workforce that lacks sufficient competence (Calderón-Rivera et al., 2024).

In Indonesia, water transportation in rural areas frequently serves as the primary means for communities to access daily necessities and engage in economic activities. However, safety in water transport operations remains a significant concern. Incidents of accidents, stemming from inadequate supervision, insufficient vessel certification, and a lack of safety equipment, pose threats to both passengers and transport operators. Notably, accidents in Lake Toba have been particularly associated with issues of overcapacity in vessels and the absence of adequate safety measures (Rahmanita et al., 2023).

Lake Towuti, covering an area of 561.1 km² and reaching a depth of 203 m, is the second-largest lake in Indonesia(Lehmusluoto et al., 1997). The ferry services on Lake Towuti connect various regions surrounding the lake in the Towuti District of South Sulawesi, as well as several villages in Southeast Sulawesi.

The traditional ships known as raffs play a significant role in supporting community activities. Initially, these vessels were intended for the transportation of timber from the opposite shore of Lake Towuti around the year 2015. However, following the prohibition of illegal timber transport, Raff has transitioned to serve the community by facilitating both cargo and passenger transport. In terms of navigation safety regulations, the operation of traditional ships on Lake Towuti does not yet meet the required safety standards, as these vessels currently lack the necessary ship certification documents (Puriningsih et al., 2022).

The study of water transportation safety in Lake Towuti remains significantly limited. Although there have been related investigations, a comprehensive analysis utilizing the MICMAC and MACTOR methods in this context has yet to be conducted. This research aims to assess the safety conditions of ferry transportation on Lake Towuti and to identify the factors influencing navigation safety. By employing the MICMAC and MACTOR approaches, this study aspires to provide a more thorough understanding of the key variables affecting safety and to establish a more effective framework for sustainable water transportation in Indonesia, particularly in Lake Towuti.

2. Literature review

The safety of water transportation is a significant issue that has been the subject of research from various perspectives. In a theoretical context, studies on water transportation safety frequently concentrate on risk management, which aims to identify and assess risks that could potentially lead to accidents (Xu et al., 2023). In various countries, regulations governing maritime safety, as established by the International Maritime Organization (IMO), are designed to reduce the risk of accidents by implementing uniform standards globally (Chircop, 2017). The implementation of such regulations often encounters challenges, particularly in developing countries, where inadequate oversight and infrastructure heighten the risk of accidents.

Empirical studies indicate that the causes of water transportation accidents are highly diverse, influenced by local conditions and the type of transportation employed. For instance, research conducted by Bowo et al. (2020) in Indonesia, has revealed that technical factors, such as machinery failures, along with human factors, including insufficient training of crew members, significantly contribute to accidents in inland waters (Bowo et al., 2020). This study also emphasizes the significance of regular vessel maintenance as a crucial factor in enhancing safety, as poorly maintained ships are more likely to experience operational failures (Sánchez-Beaskoetxea et al., 2021).

External factors, such as extreme weather conditions, also play a significant role in maritime accidents. Research conducted by Wang and Yin (2020) in China emphasizes that, in addition to technical factors, weather conditions such as storms and dense fog are also primary causes of these incidents (Wang and Yin, 2020). In

Lake Towuti, strong winds in the afternoon restrict the operating hours of traditional boats. This observation aligns with the research conducted by Christodoulou (2020), which indicates that accurate weather information is crucial for minimizing the risk of accidents in inland waters (Christodoulou et al., 2020).

One often overlooked factor in safety analysis is the weaknesses present in the regulatory and oversight framework. Xu (200) in their study on water transportation in Vietnam emphasizes the significance of strengthening the regulatory framework and enhancing institutional capacity to mitigate water transportation accidents (Xu et al., 2021). Without effective oversight, ship operators often neglect safety standards in pursuit of economic gain. The competence of the crew is also a crucial element in ensuring safety in maritime transportation. Research conducted by Kim et al. (2022) indicates that human error frequently serves as a primary cause of maritime accidents, particularly when crew members lack adequate training in safety procedures (Kim et al., 2020). This is further supported by Shanty's findings (2020), which highlight that the lack of crew competence and fatigue significantly contribute to maritime accidents (Shanty et al., 2020). Insufficient training and safety certification can elevate the risk of accidents, as observed in the context of Towuti Lake (Puriningsish, 2022).

A commonly employed safety management approach is risk analysis, which aims to identify potential hazards and assess their impact on transportation operations. Kretschmann (2020) developed a structured framework for identifying, analyzing, and predicting maritime risks (Kretschmann, 2020).

In the analysis of water transportation safety, various methods have been developed, each with its advantages and limitations. Failure Mode and Effect Analysis (FMEA) and Fault Tree Analysis (FTA) are frequently employed in maritime accident analysis. By identifying the root causes of failures, FMEA and FTA can assist in preventing emergencies and ensuring the continuity of water transportation services (Boryczko et al., 2022).

The Bow-tie method is also employed to assess transportation safety risks (Arici, 2020). This method integrates both qualitative and quantitative approaches to illustrate the primary causes of accidents and the corresponding mitigation measures. However, similar to Fault Tree Analysis (FTA), this method is limited in its ability to address cases that involve numerous variables with high interdependencies among factors (Shafiee et al., 2019).

The MICMAC method (Matrix of Crossed Impact Multiplications Applied to Classification) and the MACTOR method (Matrix of Alliances and Conflicts) have proven to be effective in addressing the complexities involved in maritime safety analysis. Unlike methods such as FMEA and FTA, which primarily focus on the direct causes of accidents, MICMAC is capable of identifying the interrelationships among variables that impact safety. For instance, MICMAC examines how factors such as vessel certification, crew competence, weather conditions, and safety oversight influence one another both directly and indirectly (Bauk and Ntshangase, 2023).

MICMAC offers a systematic approach to identify the key factors that should be prioritized in enhancing water transportation safety. In the context of Lake Towuti, where water transport involves various stakeholders and dynamic conditions, MICMAC facilitates a more in-depth analysis of how vessel maintenance, safety

equipment, and standard operating procedures (SOP) interact with other variables, including weather conditions and crew competence (Liu et al., 2024).

The MACTOR method, on the other hand, offers a robust tool for analyzing the relationships among stakeholders within the water transportation system. It focuses on identifying alliances and conflicts among the involved actors, such as local governments, ship operators, and local communities. This method is particularly pertinent in the context of Lake Towuti, where coordination among stakeholders frequently poses a significant barrier to achieving optimal transportation safety (Jiang et al., 2019). In contrast to other methods such as Bow-tie, which primarily concentrate on technical variables, MACTOR is capable of assessing the social and political aspects that influence the effectiveness of transportation safety policies.

3. Materials and methods

3.1. Data collection

Research data was obtained from various sources, including consultations with supervisors, discussions, and interviews with informants. This included insights from the Head of the River, Lake, and Ferry Transportation Division at the East Luwu Transportation Office, as well as the Coordinator of Supervisors at Lake Towuti.

The staff from the Directorate of TSDP is involved in safety information related to lake transportation. The Head of the Sub-Unit at BPTD Class II South Sulawesi is responsible for overseeing operational safety in navigation on Lake Towuti. The Head of TSDP at BPTD Class II South Sulawesi also plays a significant role in monitoring operational safety in navigation, particularly in the lakes of South Sulawesi Province. From the Water Police of South Sulawesi Regional Police, there is a section head responsible for supervising water areas (rivers/seas) and enforcing regulations in the East Luwu Regency.

The participants in this research play a crucial role in exploring in-depth information regarding their respective contributions to maritime safety, as well as assessing the significance and impact of their roles on navigation safety. The insights gathered from these participants are anticipated to enhance the understanding of their contributions and responsibilities in maintaining operational safety in Lake Towuti.

The primary data was obtained through direct interviews and observations of operators, crew members, and passengers from various vessels operating on Lake Towuti, including Angin Mamiri 01, Angin Mamiri 02, Nayla 02, Nurul Jaya, Anugrah Abadi 02, and Asifa Jaya. The interviewed passengers were users of Angin Mamiri 01 and Angin Mamiri 02. Additionally, secondary data was gathered through a literature review from various sources, including institutional documents, relevant regulations, and literature that supports this research.

3.2. Location

This research was conducted at Towuti Lake, situated in the Towuti District of Luwu Timur Regency, South Sulawesi. Towuti Lake is one of the largest lakes in Indonesia and serves as a vital transportation route for the communities residing along its shores. The area is managed by the Transportation Office of Luwu Timur Regency.

Access to Towuti Lake is relatively distant from the provincial capital, Makassar, with an estimated travel time of approximately 12h by land. The distance from the centre of Towuti District to the lake is about 56km, with a travel time of approximately 1.5h by car.

3.3. Data analysis

To identify key variables impacting transportation management and safety in Lake Towuti, the MICMAC analysis is used to explore critical factors. Additionally, the MACTOR analysis assesses the roles and interactions of various actors involved in safety and transportation management. Together, these analyses provide a comprehensive understanding of the key variables and actor relationships necessary to establish a sustainable, safe, and efficient transportation model for Lake Towuti.

4. Results and discussion

4.1. Analysis MICMAC (Matrix of Crossed Impact Multiplications Applied to Classification)

a) MDI characteristics

This **Table 1** presents the number of 0, 1, 2, 3, 4 of the matrix and shows the rate of filling calculated as a ratio between the number of MDI values different from 0 and the total number of elements of the matrix.

Table 1. MDI characteristics matrix.

Indicator	Value
Matrix size	9
Number of iterations	2
Number of zeros	9
Number of ones	16
Number of twos	15
Number of threes	41
Number of P	0
Total	72
Fillrate	88.88889%

b) MDI stability

If it were demonstrated that any matrix must converge towards stability at the end of a certain number of iterations (generally 6 or 7 for a matrix of size 30), it would be interesting to be able to follow the evolution of this stability during successive multiplications. The classification of variables within the MDI matrix, based on their influence and dependence, is carried out by calculating the number of permutations at each iteration (see **Table 2**).

Table 2. MDI stability matrix.

Iteration	Influence	Dependence
1	96%	94%
2	100%	100%

c) MDI row and column sum

This **Table 3** allows getting information about the sums in the rows and columns of the MDI matrix.

Table 3. MDI row and column sum matrix.

No	Variable	Total number of rows	Total number of columns
1	Ship Certification	20	23
2	Ship maintenance	15	20
3	Weather Information	13	12
4	Regulation	21	22
5	Safety Equipment	17	21
6	Standard Operating Procedure	22	16
7	Crew competence	22	19
8	Navigation Aids	17	13
9	Shipping safety supervision	22	23
	Totals	169	169

4.2. MACTOR analysis (Matrix of Alliances and Conflicts: Tactics, Objectives, and Recommendations)

The MACTOR analysis is employed to assess the relationships among the various stakeholders involved in the system, including government entities, transportation companies, and local communities, as well as to examine the conflicts and alliances that arise among them in pursuit of shared objectives. (Rahardjo et al., 2023).

List objective and description

1) BPTD Class II South Sulawesi (BPTD): Policy Formulation, Preparation of Norms, Standards, Procedures, and Criteria, Implementation of Evaluation and Reporting, Implementation of Policy, Implementation of Provision of Technical Guidance and Supervision
2) Satpel Timampu Port (Satpel): Supervision, enforcement, inspection, control, and implementation of land transportation functions
3) East Luwu Regency Transportation Agency (Dishub): Operation and management
4) Meteorology, Climatology and Geophysics Agency (BMKG): Weather information provider
5) National Search and Rescue Agency (Basarnas): Search and rescue
6) Polairud Polda South Sulawesi (Polairud): enforcement of regulatory violations
7) Transportation Human Resources Development Agency (BPSDM): Training organizer

8) PT Jasa Raharja (Insurance): Passenger insurance
9) Ship Operator (Operator): Lake transportation service provider
10) Local Community (Comm.): Transportation Service Users

5. Discussion

5.1. Factors influencing navigation safety in LakeTowuti

The operations of Lake Towuti fall under the jurisdiction of the East Luwu Regency Government. However, under Law No. 23 of 2014, the safety and security of navigation are the responsibility of the Central Government, specifically through the Class II South Sulawesi Land Transportation Management Office (BPTD), which has a Port Implementation Unit (Satpel) assigned for oversight.

Supporting actors such as the Barombong Shipping Polytechnic and the Makassar Shipping Science Polytechnic (PIP) play a crucial role in enhancing the competencies of ship crews. The waters of Lake Towuti also fall under the jurisdiction of the Water Police of South Sulawesi. The coordination of accident response is managed by the Luwu Timur Search and Rescue Team. Weather information is provided by the Meteorology, Climatology, and Geophysics Agency (BMKG). Passenger insurance through PT Jasa Raharja remains limited and does not cover all vessels operating in Lake Towuti.

Based on the results of interviews and direct observations at Towuti Lake Port, several critical factors that have not been optimally addressed in supporting navigation safety have been identified, necessitating a more in-depth evaluation. **Table 4** below summarizes the factors influencing navigation safety at Lake Towuti.

Table 4. Factors influencing navigation safety.

Factor	Condition	Evident
The vessel is not certified.	The vessel has not yet obtained a safety seaworthiness certificate	The Port Authority has not yet issued the sailing approval letter
Maintenance of Vessels	Maintenance is conducted solely in the event of damage or an incident	The vessel is experiencing a leak, and the water suction pump is not operational
Weather Conditions	Weather information is sourced from social media and the internet	The operational hours of the vessel are restricted to the morning and afternoon
Regulation	The existing operational regulations are insufficient, and compliance with the regulations remains inadequate.	There are currently no operational permits for the vessel, route permits, DLKR/DLKP, or business licenses.
Safety Equipment on Board Ships	Safety equipment, such as life jackets, is insufficient	The number of life jackets is insufficient for the number of passengers; the life jackets are stored in a locked box and positioned far from the passengers
Standard Operating Procedure (SOP)	There is no record of cargo and passenger loads, nor is there a ship manifest available.	The ship's manifest is not available.
Competencies of Ship Crew.	Only two crew members possess the Basic Safety Training (BST) certification.	Due to his negligence, the ship's officer fell from the KM. Bintang Towuti.

Source: Own elaborations based on data from the interviews.

5.2. MICMAC analysis

(See **Figure 1**) According to the MICMAC score table, the condition of traditional vessels on Lake Towuti, which lack certification, significantly impacts various other variables such as vessel maintenance, the adequacy of safety equipment on board, crew competence, and safety oversight. The weather factor received a high score of 3, particularly concerning its effects on vessel certification and monitoring. Adverse weather conditions, especially strong winds in the afternoon, currently restrict the operational hours of traditional shipping to only the morning and early afternoon.

The adequacy of safety equipment on vessels (Safe) has received high scores in several areas; however, it also reveals significant deficiencies, particularly in ships that do not provide an adequate number of life jackets, which should comply with the regulations of 100% plus an additional 25% of passenger capacity (Puriningsih et al., 2022). This increases the risk in emergencies. The competence of the ship's crew has a significant impact score of 3; however, the current level of competence is considered to be low.

Meanwhile, supervision demonstrates a significant impact on other safety variables, achieving the highest scores in several areas. However, the lack of effective oversight indicates that, without stringent supervision, both operators and passengers are likely to neglect their safety.

	1 : Ctfc	2 : Mtnc	3 : Weath	4 : Reg.	5 : Safe	6 : SOP	7 : Crew	8 : Nav.	9 : Superv.
1 : Ctfc	0	3	3	3	3	1	3	1	3
2 : Mtnc	3	0	1	3	2	1	1	1	3
3 : Weath	3	2	0	1	2	1	1	1	2
4 : Reg.	3	3	1	0	3	3	3	2	3
5 : Safe	3	2	1	3	0	2	2	1	3
6 : SOP	3	3	1	3	3	0	3	3	3
7 : Crew	3	3	2	3	3	3	0	2	3
8 : Nav.	2	1	1	3	2	2	3	0	3
9 : Superv.	3	3	2	3	3	3	3	2	0

Figure 1. MDI matrix scored by experts (Micmac analysis).

5.2.1. Direct influence/dependence map

In **Figure 2**, based on the MICMAC analysis of nine variables related to navigation safety in Lake Towuti, these variables are distributed across four quadrants on the direct influence/dependence map. The Standard Operating Procedures (SOP) are located in Quadrant 1, indicating that they have low influence and dependence on other variables. Currently, there are no SOPs on traditional vessels, with no passenger or cargo records and no passenger tickets, highlighting a lack of integration and effectiveness of SOPs within the overall navigation safety system.

Quadrant 2 includes variables such as crew competence, safety oversight, compliance with safety regulations, and vessel certification, which significantly influence each other. Crew competence relies on regulations and certification, while oversight ensures adherence to these regulations. Certification and regulations form

the foundation of navigation safety, with their effectiveness contingent upon stringent oversight and crew competence.

Quadrant 3 illustrates that safety equipment and vessel maintenance are highly dependent on other factors, including oversight, regulations, and crew competence. Effective ship maintenance is influenced by regulations and the implementation of standard operating procedures in routine operations.

Quadrant 4 encompasses the variables of weather conditions and navigational aids, which impact the safety of maritime operations, although they are not influenced by other variables. Weather, as an external factor, plays a critical role, while navigational aids are essential for ensuring navigation safety.

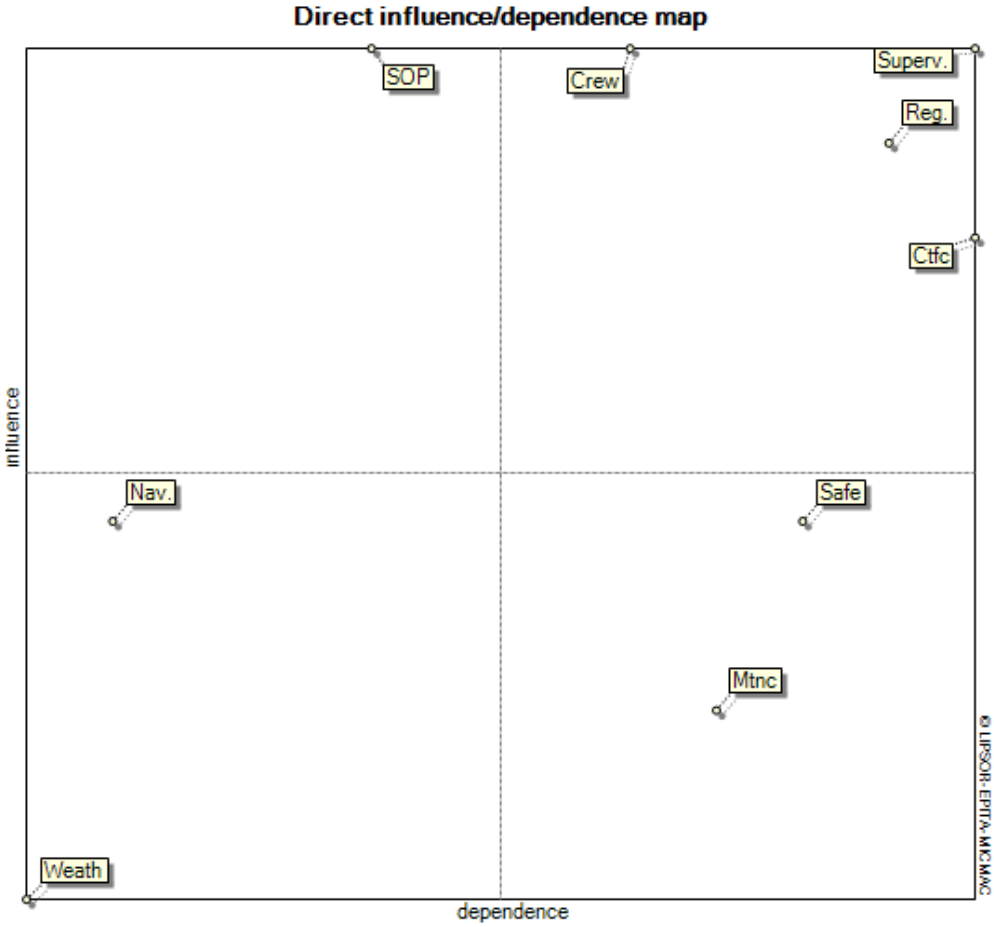

Figure 2. Direct influence/dependence map.

a) Direct influence/dependence graph

From this figure, it can be seen that SOP has the strongest influence which if fulfilled consistently will encourage other variables to become stronger. Crew, Regulation, and Supervision variables, and the direct influence graph presented in **Figure 3** illustrate a strong interconnection among safety oversight, crew competence, and navigational aids. Oversight serves as a central variable that significantly impacts overall safety, underpinned by regulations and certifications as fundamental elements. The integration of Standard Operating Procedures (SOPs), oversight, and certification is crucial for maintaining safety, particularly in adverse weather conditions.

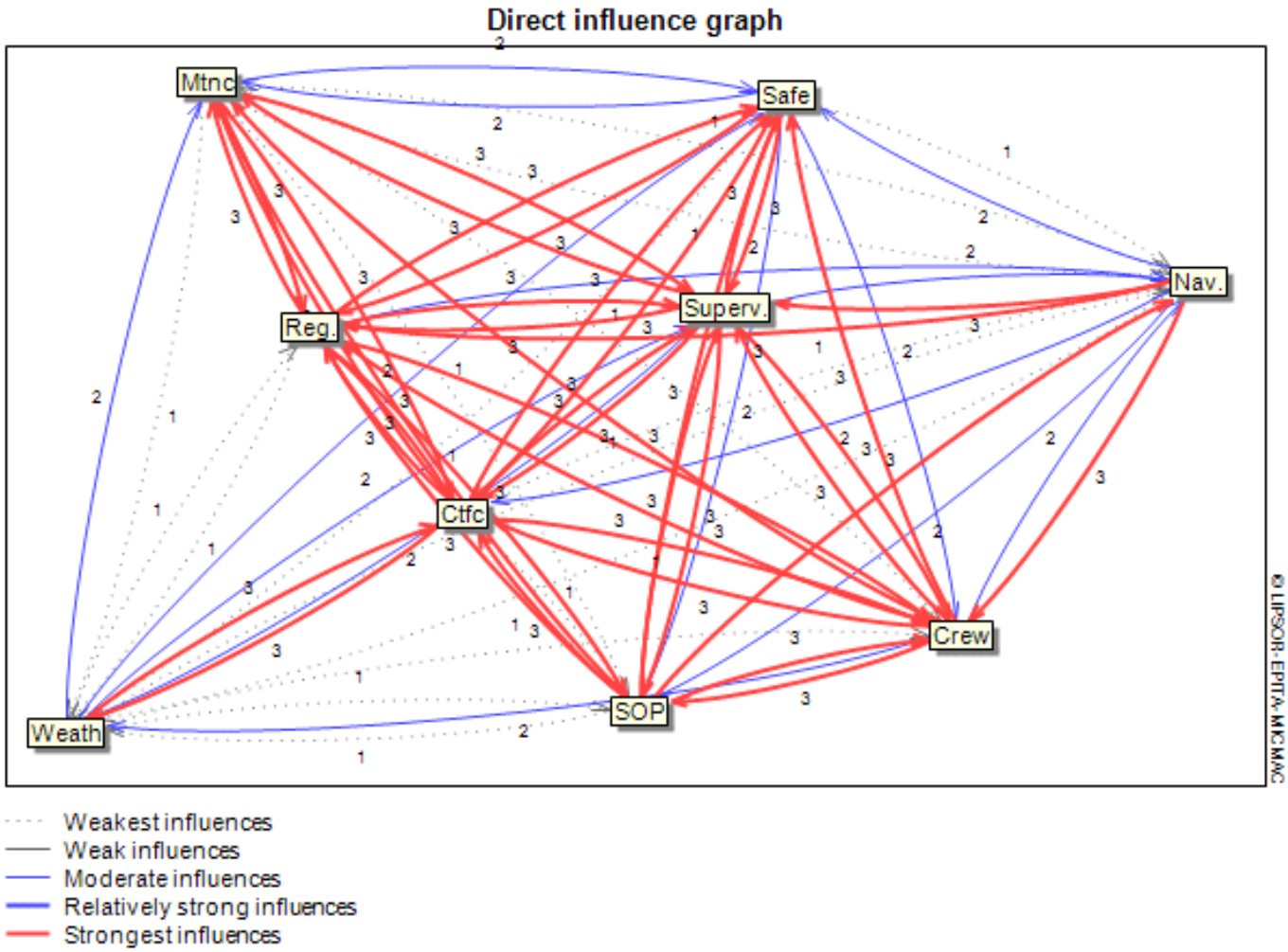

Figure 3. Direct influence/dependence graph.

b) Indirect influence graph

The Indirect Influence Graph indicates that consistent oversight will enhance compliance with regulations, which in turn exerts a significant impact (illustrated by the thick red line) on Standard Operating Procedures (SOP), crew competence, and navigation safety in Lake Towuti. Effective SOPs, skilled crew members, accurate navigation, and appropriate certifications are also critical factors in ensuring safety. This analysis underscores the necessity for a holistic approach to improving safety, emphasizing the reinforcement of oversight, enhancement of SOPs, and investment in crew training as **Figure 4**.

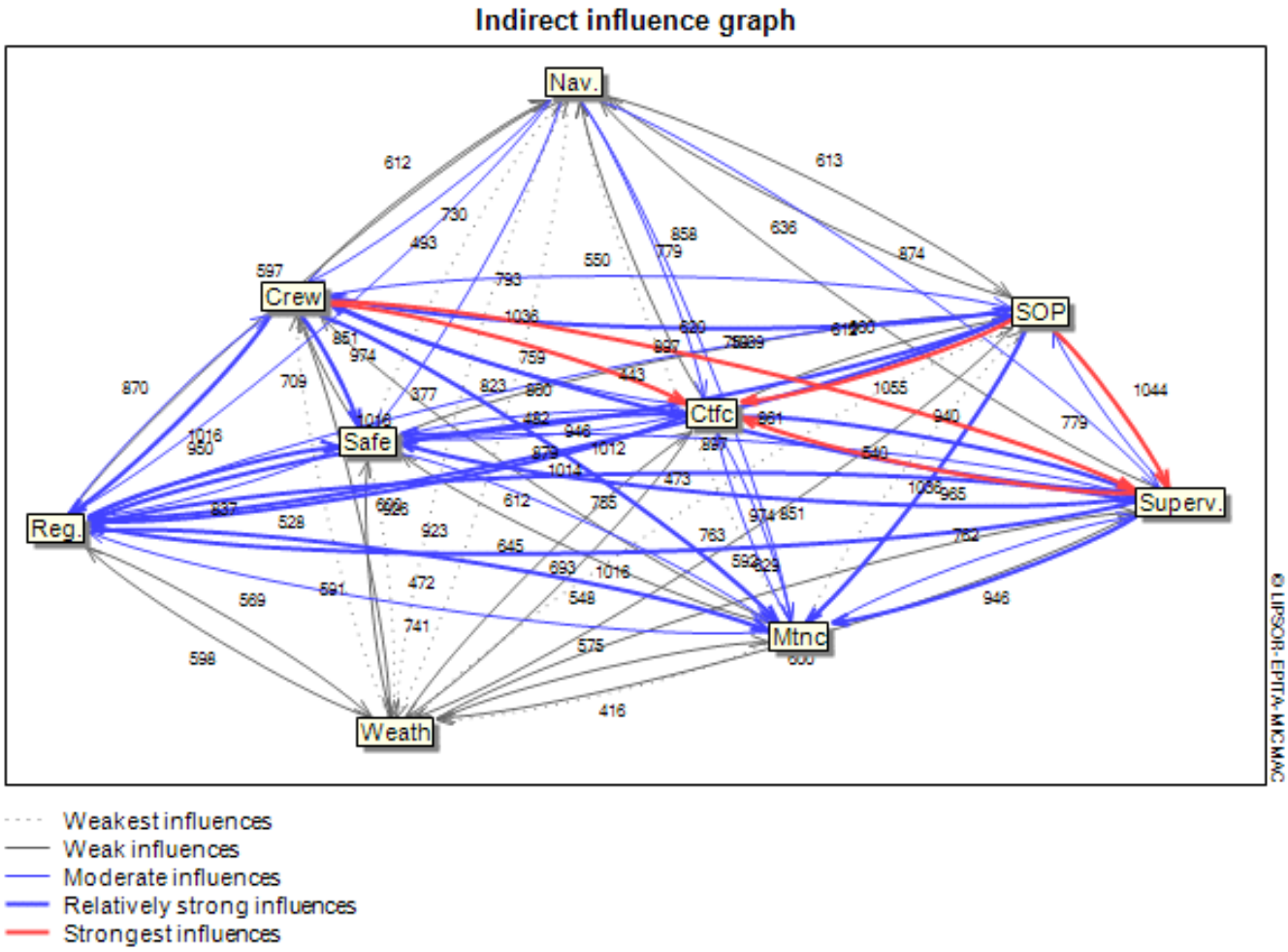

Figure 4. Indirect influence graph.

5.2.2. Mactor analysis

The MACTOR analysis is utilized to assess the interactions among stakeholders in the Lake Towuti transportation system. In **Figure 5**, each stakeholder is evaluated according to the Direct Influence Matrix (MDI). The MDI illustrates the extent of influence each stakeholder has over others. A value of 0 indicates no direct influence, a value of 1 signifies weak influence, a value of 2 represents moderate influence, and a value of 3 denotes strong influence.

MDI	BPTD	Satpel	Dishub	BMKG	Basarnas	Polairud	BPSDM	Insurance	Opertor	Comm.
BPTD	0	3	3	1	1	1	2	1	1	3
Satpel	1	0	4	1	1	1	2	1	1	3
Dishub	3	3	0	1	1	1	2	1	1	3
BMKG	1	1	1	0	1	1	1	1	1	3
Basarnas	1	1	1	1	0	1	1	1	1	3
Polairud	1	1	1	1	1	0	1	1	1	3
BPSDM	1	1	1	2	2	1	0	2	3	3
Insurance	1	1	1	1	1	1	3	0	1	3
Opertor	0	1	1	1	1	1	1	1	0	1
Comm.	3	3	3	3	3	3	3	3	1	0

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Figure 5. Matrix of Direct Influences (MDI).

In **Figure 6**, the Actor-Objective Position Matrix (2MAO) illustrates the extent of each actor's contribution to achieving maritime safety objectives. This matrix is organized in rows and columns, where the rows represent the involved actors, such as BPTD, Dishub, Basarnas, BPSDM, and Operators, while the columns represent the objectives related to enhancing maritime safety.

The numerical values within this matrix indicate the level of contribution or involvement of each actor concerning the respective objectives. The value details are as follows: 0 signifies no contribution to the objective, 1 indicates a weak contribution, 2 represents a moderate contribution, 3 denotes a strong contribution, and 4 reflects a very strong contribution. Through this matrix, actors with higher values can be identified as key players in supporting the achievement of safety objectives.

2MAO	BPTD	Satpel	Dishub	BMKG	Basarnas	Polairud	BPSDM	Insurance	Operator	Comm.
BPTD	0	4	4	2	1	2	3	2	3	3
Satpel	4	0	3	3	2	3	3	2	4	2
Dishub	4	4	0	2	2	3	3	3	4	2
BMKG	2	3	1	0	2	2	1	1	2	2
Basarnas	2	2	2	2	0	2	1	1	1	2
Polairud	3	3	3	1	2	0	1	1	4	4
BPSDM	2	3	3	1	1	1	0	1	4	2
Insurance	2	3	2	1	0	0	3	0	4	3
Opertor	4	4	4	2	2	3	3	4	0	4
Comm.	4	4	4	2	3	4	2	4	4	0

Figure 6. The matrix of valued positions Actor-Objective (2MAO).

The following outlines the relationship between the roles of stakeholders in promoting safety and efficiency in transportation at Lake Towuti, which can be examined through several key aspects, namely operating procedures, projects, missions, and existence.

1) Operating Procedures: Stakeholders such as BPTD, Satpel, and Dishub play a crucial role in ensuring the implementation of operational procedures at Lake Towuti that enhance navigation safety. A high score in this category indicates that these operational procedures are vital for the local community.
2) Project: The Satpel and Dishub stakeholders significantly contribute to sustainable transportation projects, achieving the highest scores in the implementation of navigation safety measures. The local community is also actively involved in supporting these projects due to their positive effects on the welfare and safety of users.
3) Mission: BPTD, Satpel, and Dishub exhibit a strong alignment in their missions to achieve safety and sustainability in transportation at Lake Towuti. Conversely, stakeholders such as BMKG, Basarnas, and Polairud focus more on emergency response and weather monitoring, serving a supportive role in the overall mission.
4) Existence: The local community plays a significant role in supporting the overall transportation system at Lake Towuti. Additionally, the support from BPSDM and PT Jasa Raharja is crucial for safety training and insurance, which are essential for the operational sustainability of navigation in Lake Towuti.

a) The Influences and Defenses Between Actors Map

The Influence and Dependence Map between Actors illustrates the interrelations of influence and dependence within a system, as depicted in **Figure 7**. Actors with significant influence can direct or control the actions and decisions of others, while those with high dependence require support or policies from other actors to function effectively. This map aids in understanding the dynamics of power and reliance in decision-making and operational safety within the analyzed system.

In Quadrant 1, actors such as BPTD, Polairud, Basarnas, BMKG, and Jasa Raharja exhibit very high influence but low dependence on others. They govern the policies, regulations, and operations related to maritime safety in Lake Towuti.

Quadrant 2 features actors like Dishub, Satpel, BPSDM, and local communities, who possess considerable influence yet are also highly dependent on other actors. For instance, Dishub and Satpel rely on BPTD and BMKG to effectively carry out their responsibilities.

Quadrant 3 is unoccupied, indicating that no actors exhibit both low influence and low dependence within this safety system.

In Quadrant 4, ship operators find themselves in a position of low influence but high dependence. They rely on the regulations, policies, and information provided by other actors to ensure the operational safety of traditional vessels in Lake Towuti.

A map of influence and dependence between actors is a graphic representation of actors' positions concerning influences and dependencies (direct or indirect: Di and Ii) between each other. Positions are calculated automatically by the Maxtor software.

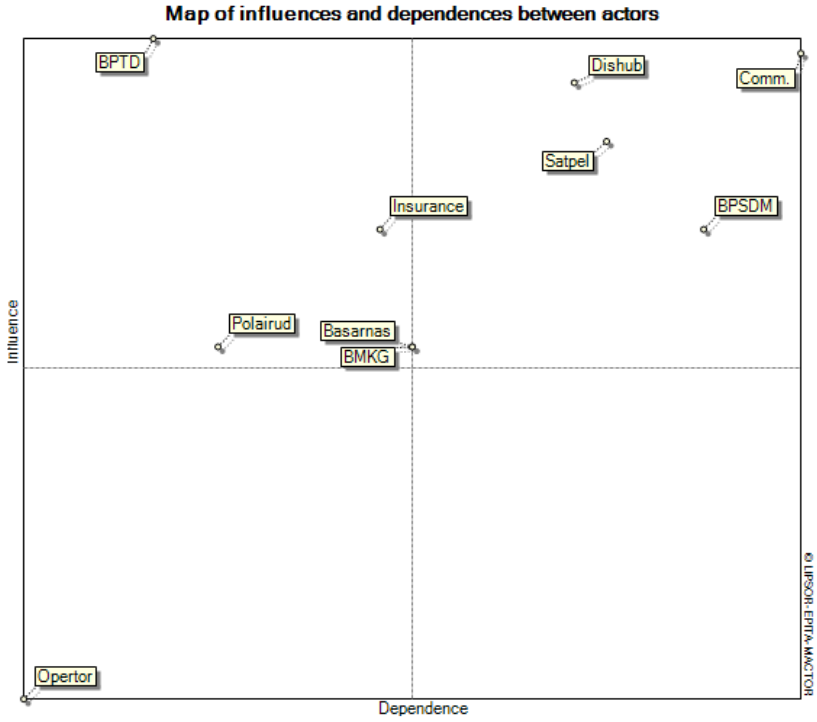

Figure 7. Map of influences and dependencies between actors.

b) Convergences between actors

In **Figure 8**, the convergence among actors highlights the high level of collaboration within the maritime safety network of Lake Towuti, where most actors

maintain strong interconnections. BPTD, Satpel, Dishub, BPSDM, Operators, and the Community play central roles in coordinating activities and ensuring the smooth operation of maritime activities. Meanwhile, Polairud, Basarnas, and PT Jasa Raharja exhibit more limited involvement, although their contributions remain significant. BMKG, characterized by several strong connections and a relatively weaker influence, plays a crucial role in providing weather information without dominating the overall collaboration.

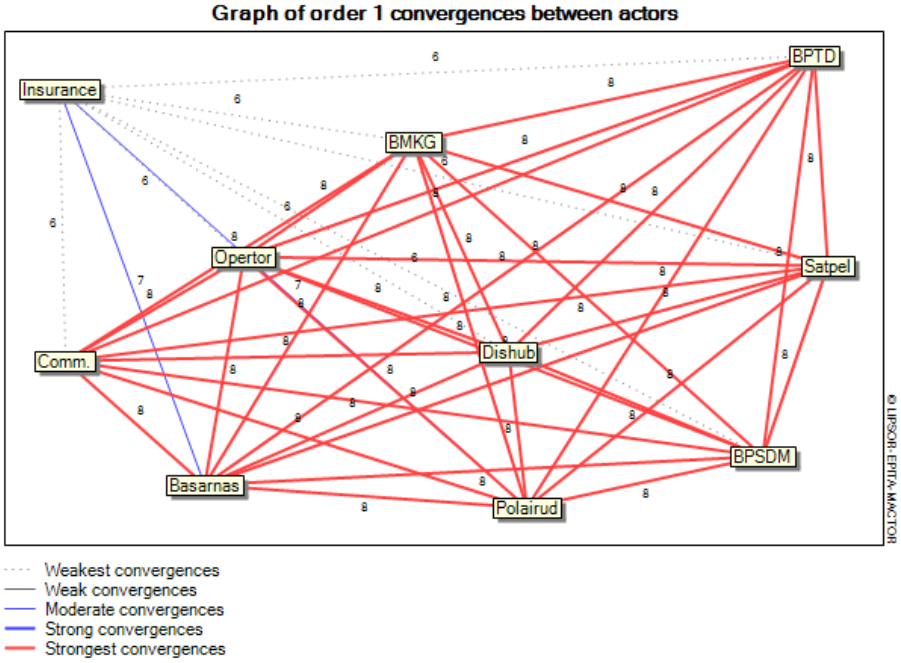

Figure 8. Convergences between actors.

5.3. Sustainable transportation model

The safety of navigation on Lake Towuti is heavily reliant on adherence to vessel certification, consistent safety oversight, enforcement of regulations, the competence of crew members, and accurate weather conditions provided by reliable agencies. Furthermore, ensuring the availability of adequate maintenance and safety equipment is crucial for enhancing safety. By focusing on these elements, maritime transportation on Lake Towuti can achieve improved safety and sustainability.

To ensure that the vessels on Lake Towuti can be certified, several important steps must be undertaken. First, the vessels must comply with the regulatory standards established by the Ministry of Transportation. Subsequently, regular audits and inspections are necessary to verify the adequacy and operational condition of safety equipment. It is also essential to require all crew members to undergo basic safety training and technical training for vessel operation. Documentation related to certification, maintenance, and crew training must be meticulously maintained, and following certification, ongoing maintenance is required to preserve the vessel's condition.

The competence of crew members is a crucial factor that significantly impacts maritime safety; however, it is currently deemed insufficient. Among the 13 traditional vessels operating in Lake Towuti, only two crew members from the Angin Mamiri 2

possess Basic Safety Training (BST) certification. Therefore, it is recommended that the East Luwu Transportation Agency collaborate with the Transportation Human Resource Development Agency to organize mass training and certification for all unqualified crew members. The implementation of subsidies, enhanced outreach efforts, and more rigorous oversight are essential to guarantee that only qualified crew members holding a certificate of competence (SKK) are permitted to operate vessels on Lake Towuti.

The analysis results from MICMAC indicate that supervision has a significant direct and indirect impact on maintenance, regulation, and safety, highlighting its importance in the prevention of accidents in Towuti.

The MICMAC analysis indicates that the current Standard Operating Procedures (SOP) have a limited impact due to inadequate integration within the safety management system at Lake Towuti, resulting in unstructured and unsafe operations. The East Luwu District Transportation Office, as the manager of Towuti Port, has not established SOPs for the management of Lake Towuti's port, including operational SOPs for traditional vessels. The East Luwu District Transportation Office needs to form an SOP Development Team in collaboration with the South Sulawesi Class BPTD. The subsequent steps should include conducting socialization and training for vessel operators, along with regular monitoring and evaluation.

The direct influence map derived from the MICMAC analysis reveals a strong interconnection among safety oversight, crew competence, vessel certification, and regulations, all of which have a direct impact on maritime safety. Although currently weak, Standard Operating Procedures (SOP) possess the potential to enhance safety if supported by appropriate oversight and compliance. The indirect influence chart emphasizes that effective oversight will bolster adherence to regulations, thereby reinforcing the implementation of SOPs, crew competence, and navigational safety. The Causal Loop Diagram (CLD) highlights key actors and critical relationships necessary for ensuring sustainable navigational safety in Lake Towuti, as illustrated in **Figure 9**. The most significant factor is vessel certification, which ensures that vessels meet safety standards concerning construction, maintenance, crew competence, and safety equipment

The South Sulawesi Class II Land Transportation Management Center is tasked with the certification of vessels, conducting inspections, and monitoring cargo loading to prevent overloading. Additionally, this centre is responsible for the installation of Navigational Aids (SBNP) to ensure safe navigation routes. The East Luwu District Transportation Office regulates the operational permits for traditional vessels operating in Towuti Lake. To enhance compliance among operators regarding safety regulations, it is essential to involve the Water Police (Polairud) with operators who frequently engage in risky practices that could jeopardize passenger safety.

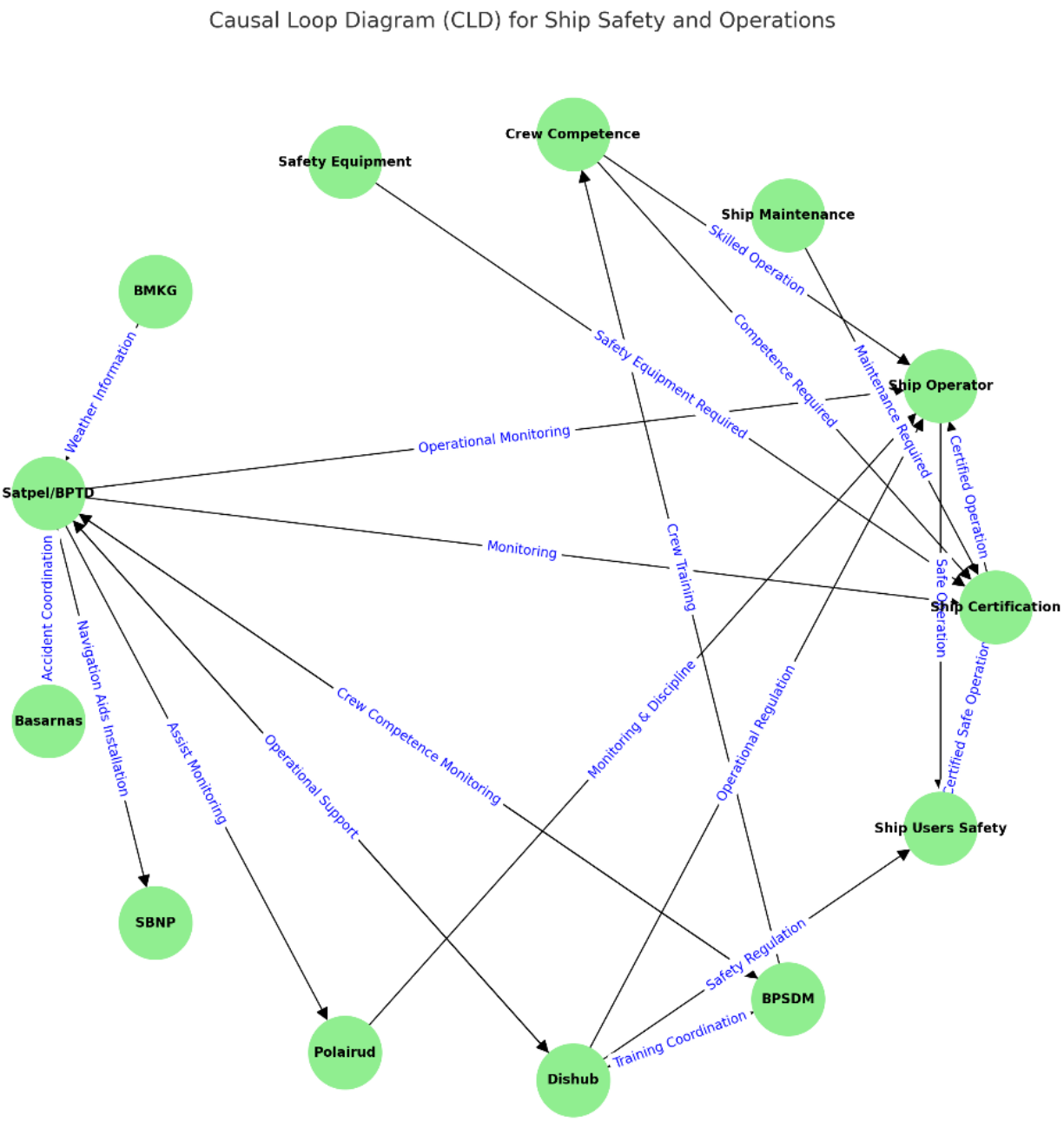

Figure 9. Causal Loop Diagram (CLD) for ship safety and operations.

5.4. The implications and contributions of the MICMAC-MACTOR method

The approach proposed in this research, which combines MICMAC (Matrix of Crossed Impact Multiplications Applied to Classification) and MACTOR (Matrix of Alliances and Conflicts: Tactics, Objectives, and Recommendations), holds significant potential for application in other contexts of water transportation systems, particularly for the management of lakes in Indonesia, where optimization remains insufficient (Jiang et al., 2019).

Through the analysis of variable interdependence, MICMAC aids in identifying how the lack of ship certification and safety oversight can affect other aspects, such as the deficiency of safety equipment on vessels. These findings are highly pertinent for

offering improved recommendations to enhance the regulatory framework in the maritime transportation sector.

Through the analysis of variable interdependence, MICMAC aids in identifying how the lack of ship certification and safety oversight can affect other aspects, such as the deficiency of safety equipment on vessels. These findings are highly pertinent for offering improved recommendations to enhance the regulatory framework in the maritime transport sector (Jiang et al., 2019). In contrast to other methods such as Bow-tie, which primarily concentrate on technical variables, MACTOR is capable of assessing the social and political aspects that influence the effectiveness of transportation safety policies.

When applying the MICMAC-MACTOR model for transportation safety analysis at Lake Towuti, it is crucial to consider the ethical implications arising from the recommendations produced. Three primary aspects require evaluation: social justice, environmental sustainability, and economic feasibility.

The enhancement of transportation safety at Lake Towuti has a direct impact on the sustainability of traditional boat operators' businesses as well as the economy of the communities surrounding the lake's shores. Lake Towuti is recognized as the largest producer of pepper in South Sulawesi Province.

The proposed model can also assist in identifying environmentally friendly transportation practices, such as the use of more efficient and eco-friendly boats, as well as proper waste management. Regulations concerning vessel safety may lead to more sustainable practices and a reduction in negative impacts on lake ecosystems. This will be crucial for preserving biodiversity and supporting the long-term sustainability of water resources.

The implementation of the MICMAC-MACTOR model must also take into account the economic impact of the recommendations produced, particularly concerning local transportation operators. Enhancements in safety often necessitate investments in training, maintenance, and safety equipment, which can increase the financial burden on operators who are already functioning with narrow profit margins. The government could offer subsidies or financial assistance to support traditional vessel operators in equipping their ships with safety gear and providing training for their crew.

6. Conclusion

The combination of MICMAC and MACTOR analyses demonstrates that the success of sustainable transportation in Lake Towuti is significantly influenced by technical factors such as vessel certification, vessel maintenance, and operational oversight, as well as the collaborative synergy among key stakeholders, including the BPTD Class II South Sulawesi (BPTD), Satpel Timampu Port (Satpel), East Luwu Regency Transportation Agency (Dishub), and the Transportation Human Resources Development Agency (BPSDMP). Support is also provided by the Polairud of the South Sulawesi Police (Polairud), the Meteorology, Climatology and Geophysics Agency (BMKG), the National Search and Rescue Agency (Basarnas), and PT Jasa Raharja (Insurance). A coordinated strategy among these variables and key actors will enhance the safety and sustainability of transportation in Lake Towuti, thereby

ensuring smooth and secure operations for all parties involved. The findings from the MICMAC and MACTOR analyses in Lake Towuti offer valuable insights that can be applied to other lakes in Indonesia, particularly those facing challenges in safety and compliance with inland lake transportation regulations.

In comparison to similar studies, the MICMAC method excels in mapping causal relationships among variables; however, it may be less effective in addressing non-technical variables such as social aspects. Consequently, the application of alternative methods alongside MICMAC and MACTOR will yield a more comprehensive analysis, particularly in dealing with dynamic variables and more complex qualitative aspects.

Future research will encompass a greater number of lakes in Indonesia, particularly those where port management is not yet optimized, and will extend over a longer duration. This study will integrate several analytical methods, including dynamic analysis, SWOT analysis, AHP, and fuzzy logic. The application of these diverse methodologies aims to provide a more comprehensive perspective in formulating effective and sustainable strategies.

Author contributions: Conceptualization, FSP; methodology, FSP, MIR and JM; validation, JM, MIR and MSA; formal analysis, FSP, MIR, JM and MSA; investigation, MIR, MSA and JM; data curation, FSP and JM; writing-original draft, FSP; writing-review and editing, FSP, MIR, JM and MSA; visualization, FSP; supervision, JM; project administration, FSP; funding acquisition, FSP. All authors have read and agreed to the published version of the manuscript.

Funding: Center for Research and Development of Sea, River, Lake, and Ferry Transportation, Ministry of Transportation through Decree Number: SK.5/HK.206/2/5-BLTL-2021.

Acknowledgments: We extend our gratitude to the Center for Research and Development of Sea, River, Lake and Ferry Transportation, the Ministry of Transportation, the East Luwu Transportation Agency, BPTD Class II of South Sulawesi, and Satpel Timampu Port for their assistance and collaboration. We also thank the operators and crew of Traditional Ships at Lake Towuti, the passengers of the Angin Mamiri 02 Ship, and all informants for their valuable insights and cooperation.

Conflict of interest: The authors declare no conflict of interest.

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