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STRATEGIC DEVELOPMENT OF POINT-TO-POINT GREEN SHIPPING CORRIDORS: A CASE STUDY USING THE INTERPRETIVE STRUCTURAL MODELLING AND MICMAC FRAMEWORK

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Abstract: Point-to-point green shipping corridors are specific maritime routes where the feasibility of zero-emission shipping is catalyzed through coordinated public and private actions. These corridors focus on deploying zero-emission vessels on direct transit routes, fostering sustainable fuel supply chains, and implementing harmonized regulatory frameworks that support decarbonization efforts between two designated ports within the maritime value chain. Currently, they are in the initiation stage, where stakeholders strive to establish a shared vision to enhance their conceptual clarity and align their strategic objectives within the maritime value chain. The aim of this paper is to deepen the understanding of the strategic development of point-to-point green shipping corridors by creating a systemic interrelated relationship between seven identified key constituent factors. The ISM methodology is utilized to construct the hierarchical interrelationships among the factors whereas the MICMAC methodology systematically classifies them based on their respective driving and dependent powers. The findings indicate that High Initial Investment Costs and the Availability of Alternative Fuel Networks are primary factors and drivers, impacting other factors within the hierarchial system.

Keywords: Point-to-Point Green Shipping Corridors, Sustainable Maritime Transport, Interpretive Structural Modelling.

1. INTRODUCTION

Green shipping corridors are emerging as an approach and strategy within the global shipping industry in response to the increasing imperative of maritime decarbonization. Initially introduced at the 26th United Nations Climate Change

Conference of the Parties (COP26) through the Clydebank Declaration on Green Shipping Corridors, these initiatives are designed to enhance the feasibility of zero-emission shipping through coordinated efforts between public and private sectors [UK Government 2021]. Among the various green shipping corridor models, the point-to-point green shipping corridor is particularly notable for its practical operational efficiency and clear strategic focus.

A point-to-point green shipping corridor is defined as a maritime route that directly connects two distinct ports [McKinsey & Company 2022]. Unlike network-based corridors that involve multiple ports and complex logistical systems, point-to-point corridors concentrate decarbonization efforts along a single, clearly delineated route. This focused strategy promotes targeted infrastructure development, enhances the management efficiency of zero-emission technologies, and simplifies the process of regulatory alignment.

Point-to-point green shipping corridors possess several defining characteristics that contribute to their effectiveness in promoting maritime decarbonization [Getting to Zero Coalition 2024]. Firstly, these corridors are characterized by defined endpoints, establishing distinct start and end locations. This clarity enables the precise coordination of decarbonization strategies that are tailored to the specific operational and environmental contexts of each port. Secondly, the operational simplicity inherent in point-to-point corridors reduces the complexity typically associated with multi-stop routes, thereby streamlining logistics, ensuring a consistent fuel supply chain, and facilitating the implementation of zero-emission vessel operations.

Furthermore, the focused nature of these corridors enhances the efficiency of fuel and technology deployment [American Journal of Transportation 2023]. By concentrating efforts on a singular route, alternative fuels such as methanol, ammonia, and hydrogen can be deployed more effectively, along with the requisite bunkering infrastructure, thereby accelerating the adoption of green technologies [Getting to Zero Coalition 2024]. Additionally, policy alignment is more readily achieved, as governments and regulatory bodies can harmonize environmental regulations, safety protocols, and financial incentives along a single corridor, thereby increasing both their operational and economic viabilities. Finally, limiting the corridor to two specific ports mitigates investment risks by creating more predictable demand and supply conditions, which in turn fosters a stable environment for private sector participation [DNV 2023].

Currently, these corridors are in the initiation phase, with critical activities including the formation of a core consortium of stakeholders, the alignment on a unified vision, and the selection of targeted shipping routes [Getting to Zero Coalition 2024]. Given their inherent characteristics, point-to-point green shipping corridors are well-suited for strategic development, while effective collaboration during the initiation phase can establish a robust foundation for the subsequent planning, execution, and operational stages, thereby advancing the global transition toward sustainable, zero-emission maritime transport. The International Maritime Organization (IMO), through its revised Greenhouse Gas (GHG) Strategy adopted in July 2023, acknowledges point-to-point green shipping corridors as a crucial approach in accelerating maritime decarbonization. In alignment with its goal of achieving net-zero emissions by 2050, the IMO endorses the development of designated shipping corridors that promote the integration of zero-emission technologies [Global Maritime Forum 2023]. The IMO actively supports the development of point-to-point green shipping corridors through various initiatives. The Future Fuels and Technology Project, a collaboration between the Government of the Republic of Korea and the IMO, seeks to reduce GHG emissions from international shipping by advancing the adoption of alternative fuels and innovative technologies [IMO 2025]. The project develops key knowledge resources, including the Zero-Emission Shipping Mission's Green Shipping Corridor Tracker; an interactive platform that maps green shipping corridor initiatives and provides current progress updates. This approach is facilitated through harmonized regulatory frameworks and collaborative efforts between public and private sector stakeholders. The role of green shipping corridors was further emphasized in the lead-up to the Marine Environment Protection Committee’s 80th session (MEPC80), where industry-led pilot projects demonstrated their potential to accelerate the transition to low-carbon maritime transport. The IMO views these initiatives as essential for scaling the adoption of alternative fuels, optimizing operational efficiency, and aligning global shipping practices with international climate objectives

However, there is a scarcity in the maritime literature regarding actionable representations of how these corridors should be developed, particularly with respect to their key elements: high initial investment costs, the availability of alternative fuel networks, alignment of regulatory and political frameworks, technological standardization and interoperability, development of infrastructure capacities, stakeholder coordination, and stable market demand [Admiralty 2023; DNV 2023; Getting to Zero Coalition 2024]. To bridge the identified gap, this paper employs the Interpretive Structural Modelling (ISM) and MICMAC (Cross-Impact Matrix Multiplication Applied to Classification) methodologies to systematically model the complex interrelationships among these factors, thereby providing a clear pathway for the effective development of point-to-point green shipping corridors. ISM is a qualitative method that helps organize and clarify the complex relationships among various factors.

In contrast, MICMAC analysis generates a graphical representation that categorizes the factors based on their driving and dependence powers [Ahmad et al. 2019]. In this study, MICMAC analysis is employed to classify and validate the factors identified through ISM, thereby underpinning the results and conclusions. The proposed model aims to offer insights for policymakers, port authorities, and shipping companies, as well as other relevant stakeholders within the maritime value chain by systematically mapping the interdependencies among key factors, thereby providing a clearer pathway for strategic decision-making and the effective understanding of point-to-point green shipping corridors.

Thus, the main goals of the study are as follows: (1) state the increasing significance of point-to-point green shipping corridors in advancing maritime transport decarbonization; (2) identify key factors via comprehensive literature reviews to systematically map the interrelationships among the key factors using the ISM and MICMAC methodologies; (3) provide a strategic framework for effective decision-making in sustainable, zero-emission maritime transport; (4) bridge the gaps in the existing literature by integrating the qualitative methodologies with practical implications, while offering actionable recommendations for policymakers, port authorities, and industry stakeholders; and (5) outline future research directions for the quantitative validation of the proposed framework.

This paper is organized into five main sections. The first section, the Literature Review, critically assesses existing research on green shipping corridors to identify the key factors necessary for their development. The subsequent section, Methodology, outlines the analytical framework employed in this study. It provides a detailed explanation of the ISM approach, including its relevance, data collection procedures, and sequential analytical steps. Next, the Results and Discussion sections present the outcomes of the ISM and MICMAC analyses, detailing the hierarchical structure of factors and their interdependencies, and discusses the implications of these findings in addressing the challenges associated with point-to-point corridors. Finally, the Conclusion section summarizes the key insights of the study, and underscores its contributions to the field.

2. LITERATURE REVIEW

The development of point-to-point green shipping corridors faces several interconnected challenges, as will be briefly discussed here in the literature review.

The early stages of point-to-point green shipping corridors necessitate the integration of innovative technologies and infrastructure, which require significant upfront financial commitments and high initial investment costs [Ismail et al. 2024]. This financial burden poses a considerable challenge for port operators. Moreover, traditional financial institutions are often reluctant to fund such initiatives due to uncertainties regarding profitability and the absence of a clearly defined repayment pathway.

The availability of alternative fuel networks presents a major bottleneck for implementing low-emission fuels in point-to-point green shipping corridors [Jesus et al. 2024]. The current infrastructure for ammonia and hydrogen bunkering is still under development, with limited cost data available. While such solutions as flexible and mobile floating bunkering terminals have been proposed to address these issues, alternative fuels continue to face challenges in terms of price competitiveness and regulatory support. Increased central government involvement in port governance is critical for aligning the regulatory and political frameworks in the implementation of point-to-point green shipping corridors [Lee and Song 2023]. This shift requires effective collaboration among central and local governments plus port authorities, as exemplified by the integrated approach used in the 6th Generation Port (6GP) model, combining governance, technology, and resilience. The 6GP model constitutes an advanced framework that integrates smart technologies, resilient operations, and robust governance. It highlights the need for central government support to address challenges like COVID-19, digitalization, and decarbonization that often exceed local capacities. By combining a smart technology platform with resilient operational systems and tailored governance, the 6GP model aims to enhance port efficiency, sustainability, and adaptability in a dynamic global environment [Lee and Song 2023]. By integrating smart technologies, resilient operations, and robust governance, the 6GP model enables efficient stakeholder coordination to implement point-to-point green shipping corridors and promote a sustainable, decarbonized maritime network.

The successful implementation of point-to-point green shipping corridors hinges on achieving technological standardization and interoperability [Lee and Song 2023]. This goal requires robust stakeholder collaboration to develop a standardized green infrastructure, including zero-emission ship construction, consistent green fuel consumption protocols, efficient delivery methods, and dedicated green fuel refueling facilities at ports. Developing infrastructure capacities for point-to-point green shipping corridors centers on three critical components: zero-emission ship construction, green fuel production and delivery systems, and green fuel refueling facilities at ports [Lee and Song 2023]. However, these advancements demand significantly higher operational and capital investments compared to conventional fossil fuel-based shipbuilding, thereby underscoring the financial challenges inherent in transitioning to sustainable maritime logistics.

A fuzzy Analytic Hierarchy Process (AHP) analysis was conducted to prioritize criteria for establishing a point-to-point green shipping corridor between the ports of Sines and Luanda [Bengue et al. 2024]. The findings indicate that stakeholder engagement, with a weight of 0.731, is the most critical criterion, underscoring the need for coordinated efforts to overcome transboundary challenges, share knowledge, and harmonize standards in sustainable maritime corridor development. In addition to the corridor connecting the ports of Sines and Luanda, other point-to-point green shipping corridors have been established worldwide. The green and digital shipping corridor between Rotterdam and Singapore represents an innovative initiative designed to cut emissions along the 15,000-kilometer route linking these two ports. The project aims to reduce emissions from large container vessels by at least 20% by 2030 by encouraging the use of low- and zero-carbon maritime fuels. This effort is driven by a collaborative network of 25 partners, who together manage over 90 major container ships on the route [Port of Rotterdam 2024]. The green shipping corridor between Sweden and Belgium includes the ports of Gothenburg, North Sea Port, and Det Forenede Dampskibs-Selskab (DFDS), with plans to introduce at least two ammonia-powered roll-on/roll-off vessels by 2030. This corridor has the potential to connect 11 European countries through integrated maritime, road, and rail networks, advancing the goal of near-zero emission transport [North Sea Port 2024].

Stable market demand is crucial for point-to-point green shipping corridors, as the market and policy environment supports the adoption of zero-carbon fuels and shipping solutions [Zhang and Feng 2024]. These corridors rely on demand mobilization strategies, such as customer commitments and the alignment of policy incentives with stakeholder engagement, to secure investments in zero-emission technologies and infrastructure. Public subsidies and cap-and-trade mechanisms can offset the substantial initial costs of green shipping initiatives, emphasizing the pivotal role of the ports' business and governance models in translating these incentives into operational efficiency [Wang, Cheng and Zhen 2023]. While natural market mechanisms, such as customer-driven demand, may partially motivate shipping firms, robust regulatory factors and economic stimuli remain essential for surmounting the high capital barriers and achieving long-term profitability [Christodoulou and Cullinane 2021]. Collaboration between regulatory bodies and industry stakeholders can fill the gaps left by weak market forces, as illustrated by an "orchestration" framework [Lister, Poulsen and Ponte 2015]. Real options analysis helps shipowners defer high-risk retrofitting decisions until conditions become more favorable, linking the return on investment to shifting fuel price differentials [Acciaro 2014a, b]. Finally, integrating intrafirm, interfirm, and learning-based capabilities within maritime corporate governance models can bolster sustainable operations and secure the funding sources necessary for large-scale decarbonization projects [Yuen et al. 2019].

From the perspective of point-to-point green shipping corridors, as identified by the literature review, several key factors are critical for achieving effective decarbonization across interconnected ports. High initial investment costs present a significant barrier, as establishing the necessary alternative fuel infrastructure at both ports demands substantial capital expenditure [Ismail et al. 2024]. Additionally, the availability of alternative fuel networks is crucial, given that a reliable fuel supply at both terminals is necessary to prevent operational vulnerabilities [Jesus et al. 2024]. Effective alignment of the regulatory and political networks is essential for harmonizing policies across different jurisdictions, thereby facilitating smoother implementation of the corridor [Lee and Song 2023]. Technological standardization and interoperability ensure that innovations in zero-emission technologies are compatible between ports, though focusing these efforts may limit scalability [Lee and Song 2023]. Robust infrastructure capacities are also indispensable, as both ports must develop comprehensive facilities for fuel production, supply, and vessel servicing [Lee and Song 2023]. Furthermore, localized stakeholder coordination, involving port authorities, local governments, and shipping companies, is necessary to manage the complexities of cross-port operations [Bengue et al. 2024]. Stable market demand at both the origin and destination ports is vital for sustaining the operational viability of the corridor [Zhang and Feng 2024]. By addressing these factors through coordinated efforts between the participating ports, a viable model for sustainable maritime operations in point-to-point green shipping corridors can be established.

Within point-to-point green shipping corridors, these insights translate into strategic and operational practices aimed at overcoming the high initial investments and limited market mechanisms typical of route-specific decarbonization efforts. For instance, public subsidies and cap-and-trade policies [Wang et al. 2023] can specifically target the two ports involved in a corridor, helping them build the infrastructure needed for zero-emission fuels or advanced operational systems. In this setting, governance models play an equally critical role, requiring both ports and relevant authorities to collaborate on tailored economic incentives that encourage shipping firms to adopt low-carbon technologies [Christodoulou and Cullinane 2021]. Moreover, a regulatory “orchestration” framework strengthens corridor-specific initiatives by bringing together stakeholder interests, such as port authorities, shipping lines, and policy-makers, thereby compensating for the absence of sufficient natural market mechanisms [Lister, Poulsen and Ponte 2015].

On the financial side, real options analysis can guide investment decisions for corridor-focused technologies (e.g., LNG retrofits or zero-emission vessel upgrades), allowing operators to wait until certain fuel price thresholds are met before committing capital [Acciaro 2014a, 2014b]. Finally, sustainable operations along a defined route benefit from a governance structure that integrates intrafirm, interfirm, and organizational learning capacities, helping to align corridor-specific initiatives, such as alternative fuel supply chains or stakeholder engagement efforts, with overall business performance [Yuen et al. 2019]. By applying these practices to point-to-point green shipping corridors, key decarbonization drivers become more targeted and effective, enabling a cohesive framework that addresses both the economic and regulatory challenges of zero-emission maritime routes.

3. METHODOLOGY – THE ISM AND MICMAC TECHNIQUES

Interpretive Structural Modelling (ISM) is a methodological approach that converts ambiguous and inadequately articulated mental models of systems into explicit, well-defined representations, thereby supporting various analytical applications [Sushil 2012]. This technique systematically organizes factors according to their interrelationships, as determined by expert judgment, and utilizes computational tools grounded in matrix algebra and graph theory to construct visual models. In this study, we adopt the methodological framework [Ahmad and Qahmash 2021] to streamline and automate both the ISM and MICMAC techniques using SmartISM software, developed by the same authors. The implementation of these techniques involves eight critical steps that are described in detail in the following subsections.

Figure 1 represents the systematic, step-by-step approach of the entire study.

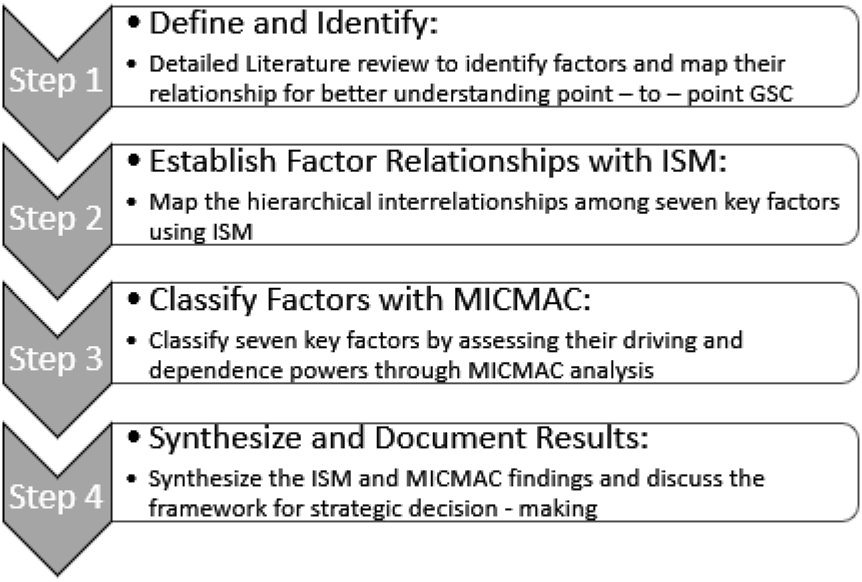

Fig. 1. The Four-Step Systematic Approach for Assessing Interrelationships in Point-to-Point Green Shipping Corridors

Source: authors' work.

Figure 1 describes the four crucial steps utilized within the paper:

- **Step 1. Define and Identify.** A thorough literature review to determine the key factors relevant to point-to-point green shipping corridors (GSC). This step clarifies the study's scope and objectives, establishing a baseline for subsequent analysis.
- **Step 2. Establish Factor Relationships with ISM.** The application of Interpretive Structural Modeling (ISM) to observe how the identified seven factors factors interact, resulting in a hierarchical structure that indicates the relative influence each factor exerts on the others.
- **Step 3. Classify Factors with MICMAC.** Employment of the MICMAC technique to determine the driving and dependence powers of each factor, highlighting the critical drivers and the most dependent variables.
- **Step 4. Synthesize and Document Results.** Integrate the findings from ISM and MICMAC into a cohesive framework, providing insights for strategic decision-making in the development and implementation of point-to-point GSCs.

Overall, this step by step approach provides a comprehensive and systematic guideline for analyzing and developing point-to-point green shipping corridors, thereby guiding strategic decision-making in sustainable maritime transport.

3.1. Fundamental Components of the Interpretative Structural Modelling Methodology

Identifying the study's elements or factors is essential, as it involves delineating their scope, objectives, and potential metrics. Typically, these elements are determined using a combination of methodologies, including literature reviews, expert consultations, and surveys. Furthermore, common analytical techniques for identifying elements comprise thematic analysis, content analysis, SWOT analysis, and the Delphi technique. It is imperative to clearly specify the source, conceptual understanding, and interpretation for each variable [Kumar and Singh 2019].

3.2. Decision-Makers (DMs)

DMs are fundamental to the ISM process, as both their methodology and outcomes rely on their expertise. The selection of DMs is guided by three primary criteria: size, expertise, and diversity. It is essential that the group represents all pertinent stakeholders to ensure a comprehensive and expert understanding of the variables under investigation. The literature indicates that DM groups range in size from 2 to 120 members, with a median of 11 [Tarei, Chand and Gupta 2021].

3.3. Structural Self-Interaction Matrix (SSIM)

The SSIM delineates the relationships among elements using four distinct symbols:

- **Symbol V:** Indicates that Factor x influences Factor y.
- **Symbol A:** Indicates that Factor y influences Factor x.
- **Symbol X:** Denotes that Factors x and y mutually influence each other.
- **Symbol O:** Signifies that there is no relationship between Factors x and y.

Decision-makers establish these relationships through pairwise comparisons of the variables. If nnn represents the number of factors in the study, the total number of comparisons is given by $n(n-1)/2$. The resulting output is an n by n matrix that encapsulates the specified symbolic representations.

3.4. Reachability Matrix (RM) and Final Reachability Matrix (FRM)

The RM is the binary representation of the SSIM. In this process, the four symbolic states are converted into binary values as follows [Attri, Dev and Sharma 2013]:

- **Symbol V:** Replaced with 1.
- **Symbol A:** Replaced with 0.
- **Symbol X:** Replaced with 1.
- **Symbol O:** Replaced with 0.

These binary values are also assigned to the corresponding transposed positions (from row to column and vice versa), while all diagonal entries are set to 1, reflecting the assumption that each construct influences itself. Following the conversion, the principle of transitivity is applied. For example, if factor x influences factor y and factor y influences factor z, then factor x is assumed to influence factor z. These transitive relationships are denoted with a 1* in the RM to distinguish them from the original direct relationships, thereby forming the FRM. The FRM further facilitates the determination of the driving and dependence powers of each variable by counting the occurrences of 1s and 1*s in the respective rows and columns. Additionally, the Warshall Algorithm is employed to further refine the matrix.

3.5. Level Partitioning

Level partitioning is a critical phase in developing the hierarchical structure of the factors within the ISM framework. This process, derived from the FRM [Singh and Khamba 2011]], involves three key steps:

- **Reachability Set:** Comprises the variable itself and all variables that it influences.
- **Antecedent Set:** Comprises the variable itself and all variables that influence it.
- **Intersection Set:** Represents the common elements shared by both the reachability and antecedent sets.

Variables for which the reachability set is identical to the intersection set are assigned the highest rank and subsequently removed from further iterations. This iterative process continues until all variables have been ranked, ensuring an accurate and robust ISM model.

3.6. Conical Matrix (CM) and Digraph

The CM is derived by reorganizing the rows and columns of the FRM according to the variable ranks established during level partitioning, with each variable's level appended to its corresponding row and column. This matrix forms the basis for constructing the digraph, which visually represents the hierarchical structure. In the digraph, variables are depicted as circular nodes connected by directed edges that correspond to the binary values (1s or 1*s) in the CM [Ahmad and Siddiqui 2016]. Although the digraph is a simplified representation compared to the final model, owing in part to automated transitivity calculations, it remains a valuable tool for elucidating the directional relationships among variables.

3.7. Reduced Conical Matrix (RCM) and Final ISM Model

The digraph is transformed into the final ISM model by replacing the node numbers with variable names and rendering the nodes as rectangular shapes. The model is then simplified by removing extraneous edges while preserving its hierarchical structure, variable levels, and reachability. Recognizing that errors, such as the addition of unnecessary edges or the omission of critical ones, can compromise the model‘s accuracy, the RCM algorithm was developed [Ahmad and Qahmash 2021]. This algorithm minimizes redundant edges without affecting the underlying structure, thereby ensuring an accurate and coherent final ISM model.

3.8. MICMAC Technique

MICMAC is a technique used to categorize variables by mapping them onto a two-dimensional grid, where the vertical axis represents driving power and the horizontal axis represents dependence power [Arcade et al. 2012]. The values on each axis range from 1 to the total number of variables, with the axes bisected at their midpoints to form four quadrants:

- **Autonomous variables:** Weakly connected to the system.
- **Dependent variables:** Strongly influenced by other variables.
- **Linkage variables:** Highly sensitive and interconnected.
- **Independent variables:** Serve as strong drivers with minimal dependence.

Collectively, this classification enhances our understanding of the dynamic interplay among system variables, thereby providing a critical foundation for both analytical inquiry and strategic decision-making.

4. RESULTS OF THE ISM AND MICMAC TECHNIQUES

The study's findings on the strategic framework for implementing point-to-point green shipping corridors are presented here, following the ISM methodology [Ahmad and Qahmash 2021].

4.1. Fundamental Components of the Interpretative Structural Modelling Methodology

The elements (i.e., factors) of this study were identified solely through an extensive literature review, ensuring a comprehensive understanding of and alignment with the scope of point-to-point green shipping corridors. Each component has been carefully interpreted within this context and is systematically presented in Table 1 for clarity and reference.

Table 1. Factors for point-to-point Green Shipping Corridor Development

Factor	Component Definition	Reference
High Initial Investment Costs	The deployment of alternative fuel infrastructure at both terminal ports necessitates a considerable capital investment, which can impose significant financial constraints on corridor development	[Ismail et al. 2024]
Availability of Alternative Fuel Networks	The operational efficacy of the corridor is contingent upon the consistent presence of alternative fuel networks at both ports, as any supply inconsistencies or shortages may compromise performance	[Jesus et al. 2024]
Alignment of Regulatory and Political Frameworks	Coordinating regulatory and political frameworks across two distinct jurisdictions is imperative; however, the focused nature of point-to-point corridors may facilitate streamlined local governance	[Lee and Song 2023]
Technological Standardization and Interoperability	Achieving uniformity and ensuring compatibility of emerging technologies between the two ports is essential for the effective integration of zero-emission solutions, even though it may limit scalability	[Lee and Song 2023]
Development of Infrastructure Capacities	The success of the corridor depends on each port establishing a robust infrastructure, including advanced facilities for alternative fuel distribution and zero-emission vessel servicing	[Lee and Song 2023]
Stakeholder Coordination	Effective implementation relies on the coordinated efforts of key stakeholders, such as port authorities, local governments, and shipping companies, across both ports to ensure cohesive operational strategies	[Bengue et al. 2024]
Stable Market Demand	The long-term viability of the corridor is underpinned by a steady market demand for green shipping services at both endpoints, which is critical to maintaining economic and operational sustainability	[Zhang and Feng 2024]

The components identified in Table 1 offer a foundational framework for analyzing and interpreting point-to-point green shipping corridors, ensuring that the study's objectives and methodological approach are coherently aligned.

4.2. Decision-Makers (DMs)

The survey was disseminated to a sample of 40 individuals, from which three respondents provided feedback. These respondents, constituting the expert group, are employed by a distinguished non-profit maritime research and consulting institute in Germany. They possess a diverse range of expertise in maritime logistics and green shipping initiatives, thereby offering a comprehensive and nuanced perspective on the study's elements.

4.3. Structural Self-Interaction Matrix (SSIM)

The SSIM encapsulates the expert survey feedback by systematically mapping the pairwise relationships among key challenges associated with point-to-point green shipping corridors. This analytical tool elucidates the interdependencies and hierarchical structure inherent in these challenges.

Table 2. Structural Self-Interaction Matrix (SSIM)

Factor	1	2	3	4	5	6	7
High Initial Investment Costs		V	O	V	V	V	V
Availability of Alternative Fuel Networks			V	V	V	V	V
Alignment of Regulatory and Political Networks				V	V	V	V
Technological Standardization and Interoperability					V	V	O
Development of Infrastructure Capacities						V	V
Stakeholder Coordination							V
Stable Market Demand							

As presented in Table 2, the matrix delineates the pairwise relationships among the variables, illustrating how each factor both influences and is influenced by the others. Notably, the primary driving components identified are high initial investment costs and the availability of alternative fuel networks.

4.4. Reachability Matrix (RM) and Final Reachability Matrix (FRM)

The RM, derived from the SSIM, offers a binary mapping of the interrelationships among the key factors. It elucidates how each element influences or is influenced by others within the context of point-to-point green shipping corridors.

Table 3 outlines the RM.

The RM identifies high initial investment costs and the availability of alternative fuel networks as the primary strategic drivers for implementing point-to-point green shipping corridors, each exerting the highest driving power (6) on other factors. In addition, the alignment of regulatory and political networks, with a driving power of 5, links foundational challenges to mid-level factors such as technological standardization, interoperability, infrastructure capacities, and stakeholder coordination, while dependent variables like stable market demand (driving power 1) primarily reflect outcome measures.

Table 3. Reachability Matrix

Factor	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**Driving Power**
High Initial Investment Costs	1	1	0	1	1	1	1	6
Availability of Alternative Fuel Networks	0	1	1	1	1	1	1	6
Alignment of Regulatory and Political Networks	0	0	1	1	1	1	1	5
Technological Standardization and Interoperability	0	0	0	1	1	1	0	3
Development of Infrastructure Capacities	0	0	0	0	1	1	1	3
Stakeholder Coordination	0	0	0	0	0	1	1	2
Stable Market Demand	0	0	0	0	0	0	1	1
Dependence Power	1	2	2	4	5	6	6	

The FRM is derived by incorporating transitivity into the RM, ensuring that indirect relationships among factors are systematically identified and accurately represented. This refined matrix serves as the foundational framework for establishing the hierarchical structure of the key components in point-to-point green shipping corridors.

Table 4 outlines the FRM.

The FRM confirms that High Initial Investment Costs is the primary driver, with a driving power of 7 that influences all other factors. The Availability of Alternative Fuel Networks follows, with a driving power of 6, shaping the key mid-tier challenges. Technological Standardization and Interoperability, possessing a driving power of 4, functions as an intermediary factor, influenced by High Initial Investment Costs and the Availability of Alternative Fuel Networks, while also impacting the Development of Infrastructure Capacities and Stakeholder Coordination. Finally, Stable Market Demand emerges as the most dependent variable, with a driving power of 1 and a dependence power of 7, indicating that it is largely determined by the preceding factors.

Table 4. Final Reachability Matrix

Factor	1	2	3	4	5	6	7	Driving Power
High Initial Investment Costs	1	1	1*	1	1	1	1	7
Availability of Alternative Fuel Networks	0	1	1	1	1	1	1	6
Alignment of Regulatory and Political Networks	0	0	1	1	1	1	1	5
Technological Standardization and Interoperability	0	0	0	1	1	1	1*	4
Development of Infrastructure Capacities	0	0	0	0	1	1	1	3
Stakeholder Coordination	0	0	0	0	0	1	1	2
Stable Market Demand	0	0	0	0	0	0	1	1
Dependence Power	1	2	3	4	5	6	6	

4.5. Level Partitioning (LP)

LP is employed to systematically organize the factors into hierarchical tiers based on their reachability and dependency. This approach facilitates a clear understanding of the sequential progression and interdependencies among factors within the context of point-to-point green shipping corridors.

Table 5 summarizes LP.

Table 5. Level Partitioning

Factor (Mi)	Reachability Set R(Mi)	Antecedent Set A(Ni)	Intersection Set R(Mi) ∩ A(Ni)	Level
(1) High Initial Investment Costs	1	1	1	7
(2) Availability of Alternative Fuel Networks	2	1,2	2	6
(3) Alignment of Regulatory and Political Networks	3	1,2,3	3	5
(4) Technological Standardization and Interoperability	4	1,2,3,4	4	4
(5) Development of Infrastructure Capacities	5	1,2,3,4,5	5	3
(6) Stakeholder Coordination	6	1,2,3,4,5,6	6	2
(7) Stable Market Demand	7	1,2,3,4,5,6,7	7	1

High Initial Investment Costs (MI: 1) is positioned at the highest hierarchical level (7), underscoring its role as the primary driver exerting influence over all other variables. In sequence, Availability of Alternative Fuel Networks (MI: 2) and Alignment of Regulatory and Political Networks (MI: 3) emerge as critical mid-tier drivers. Technological Standardization and Interoperability (MI: 4), Development of Infrastructure Capacities (MI: 5), and Stakeholder Coordination (MI: 6) occupy intermediary positions. Conversely, Stable Market Demand (MI: 7) is situated at the lowest level (1), emphasizing its reliance on the resolution of the previously mentioned challenges.

4.6. Conical Matrix (CM)

The CM reformulates the FRM into a structured, hierarchical format, thereby facilitating a clear visualization of both the driving forces and the dependent relationships among the variables under investigation.

Table 6 outlines the CM.

Table 6. Conical Matrix

Factor	1	2	3	4	5	6	7	Driving Power	Level
(7) Stable Market Demand	1	0	0	0	0	0	0	1	1
(6) Stakeholder Coordination	1	1	0	0	0	0	0	2	2
(5) Alignment of Regulatory and Political Networks	1	1	1	0	0	0	0	3	3
(4) Development of Infrastructure Capacities	1*	1	1	1	0	0	0	4	4
(3) Technological Standardization and Interoperability	1	1	1	1	1	0	0	5	5
(2) Availability of Alternative Fuel Networks	1	1	1	1	1	1	0	6	6
(1) High Initial Investment Costs	1	1	1	1	1*	1	1	7	7
Dependence Power	7	6	5	4	3	2	1		
Level	1	2	3	4	5	6	7		

The CM underscores that High Initial Investment Costs (MI: 1) and the Availability of Alternative Fuel Networks (MI: 2) serve as principal drivers, with driving power scores of 7 and 6, respectively. In contrast, the dependent variable, Stable Market Demand (MI: 7), exhibits the lowest driving power (1) and the highest dependence power (7), thereby representing the ultimate outcome within the system.

4.7. Reduced Conical Matrix (RCM) and Final ISM Model

The RCM refines the mapping of relationships by concentrating on the most critical connections, thereby accentuating the hierarchical structure of the variables under study.

Table 7 outlines the RCM.

Table 7. Reduced Conical Matrix

Factor	1	2	3	4	5	6	7	Driving Power	Level
Stable Market Demand	1	0	0	0	0	0	0	1	1
Stakeholder Coordination	1	1	0	0	0	0	0	2	2
Development of Infrastructure Capacities	0	1	1	0	0	0	0	3	3
Technological Standardization and Interoperability	0	0	1	1	0	0	0	4	4
Alignment of Regulatory and Political Networks	0	0	0	1	1	0	0	5	5
Availability of Alternative Fuel Networks	0	0	0	0	1	1	0	6	6
High Initial Investment Costs	0	0	0	0	0	1	1	7	7
Dependence Power	7	6	5	4	3	2	1		
Level	1	2	3	4	5	6	7		

High Initial Investment Costs (MI: 1) and the Availability of Alternative Fuel Networks (MI: 2) are identified as the primary drivers, exhibiting the highest driving powers of 7 and 6, respectively, and exerting significant influence over all subsequent challenges. Conversely, Stable Market Demand (MI: 7) is the most dependent variable, characterized by the lowest driving power (1) and the highest dependence power (7). Mid-tier variables, such as Technological Standardization and Interoperability (MI: 4) and the Development of Infrastructure Capacities

(MI: 5), function as intermediaries within the system. Consequently, addressing these foundational drivers is imperative for effectively mitigating the downstream challenges.

The final model offers a clear hierarchical framework for understanding the challenges in point-to-point green shipping corridors, as shown in Figure 2.

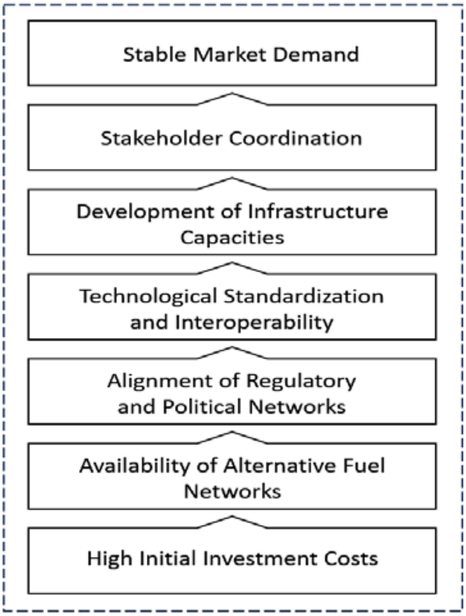

Fig. 2. ISM-Based Model for the Strategic Framework for Developing Point-to-Point Green Shipping Corridors

Source: authors' own work.

At the foundation of the model lies High Initial Investment Costs, which serves as the primary driver influencing all subsequent factors in point-to-point green shipping corridors. This factor directly impacts the Availability of Alternative Fuel Networks, a critical element that shapes the progression of the ensuing challenges. The Alignment of Regulatory and Political Networks emerges as an intermediate factor, effectively linking these foundational drivers to the operational issues inherent in the green shipping corridors. Furthermore, Technological Standardization and Interoperability significantly affect the Development of Infrastructure Capacities, as advancements in green technologies are vital for establishing sustainable corridor infrastructure.

Effective Stakeholder Coordination also plays a crucial role, necessitating close alignment among diverse stakeholders to overcome the infrastructure and technological constraints. At the top of the hierarchy is Stable Market Demand, which represents the most dependent variable reflecting the cumulative impact of the preceding challenges on the overall viability of point-to-point green shipping corridors. A more detailed analysis of the interactions among these seven factors is presented here in the Discussion section.

4.8. MICMAC Method Analysis

The MICMAC analysis systematically delineates the driving and dependent powers of the factors, offering critical insights into their influence and interdependencies within the framework of point-to-point green shipping corridors.

Figure 3 is a graphical representation of the outcomes of this analysis.

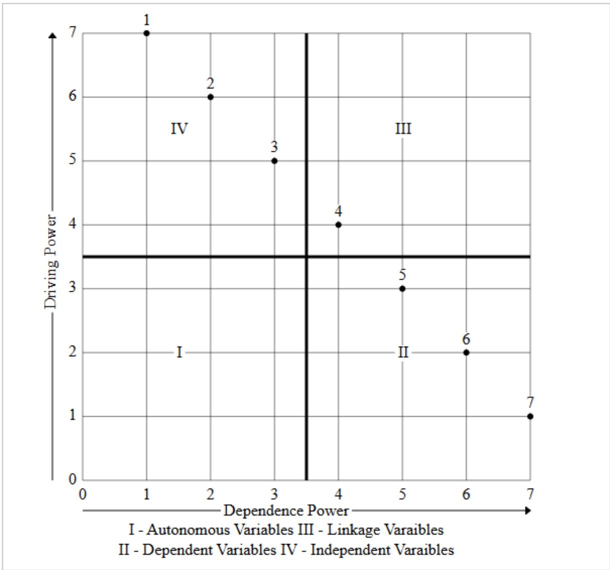

Fig. 3. MICMAC-Based Analysis of Driving and Dependent Powers in Point-to-Point Green Shipping Corridors

Source: authors' own work.

The MICMAC analysis classifies factors in point-to-point green shipping corridors based on their driving power and dependence power, organizing them into four distinct quadrants.

In Quadrant I, representing Autonomous Variables, no factors are present, which indicates that all variables within the system are interconnected. In Quadrant II, the Dependent Variables, comprising Development of Infrastructure Capacities (5), Stakeholder Coordination (6), and Stable Market Demand (7), are heavily influenced by other factors and reflect the outcomes of system enhancements. Consequently, Quadrant III, which represents Linkage Variables, includes Technological Standardization and Interoperability (4), a factor that exhibits both high driving power and significant sensitivity as both an influencer and an outcome. Lastly, Quadrant IV, the Independent Variables, comprises High Initial Investment Costs (1), Availability of Alternative Fuel Networks (2), and Alignment of Regulatory and Political Networks (3); these factors serve as the foundational elements shaping the point-to-point green shipping corridor ecosystem.

5. DISCUSSION

Stable market demand is crucial for point-to-point green shipping corridors, as supportive policies, market readiness, and effective demand mobilization strategies (e.g., customer commitments) are essential for securing investments in zero-emission technologies [Zhang and Feng 2024]. Achieving such stability requires aligning local policy incentives, fostering stakeholder collaboration, and ensuring overall market preparedness, which in turn underpins the infrastructure development and the long-term sustainability of green shipping initiatives. Stakeholder coordination is critical for point-to-point green shipping corridors, as demonstrated by Stakeholder coordination [Bengue et al. 2024] through a fuzzy AHP analysis that ranks stakeholder engagement as the highest priority (0.731), underscoring its essential role in achieving social acceptance. Effective coordination fosters collaboration among diverse entities to address transboundary challenges, harmonize standards, and share knowledge, which is vital for attracting investments and ensuring the success of sustainable maritime logistics initiatives.

The development of infrastructure capacities is fundamental for point-to-point green shipping corridors, with a focus on zero-emission ship construction, green fuel production systems, and refueling facilities [Lee and Song 2023]. However, these advancements involve significantly higher operational and capital costs than traditional fossil fuel-based systems, and overcoming these financial challenges requires targeted investments, public-private partnerships, and supportive policies to enable the transition to a sustainable maritime logistics infrastructure. Technological standardization and interoperability serve as critical linkage variables in the development of point-to-point green shipping corridors, ensuring the effective integration of zero-emission ship construction, uniform green fuel consumption and delivery methods, and dedicated refueling facilities at ports. The success of these corridors hinges on active stakeholder cooperation to establish and maintain a standardized green infrastructure [Lee and Song 2023].

Regulatory and political network alignment is a critical independent variable for point-to-point Green Shipping Corridors (GSCs), emphasizing the increasing role of central governments in port governance and the necessity for collaboration between central and local governments and port authorities [Lee and Song 2023]. Supported by the 6GP (6GP) model, which integrates governance, technology, and resilience, this alignment facilitates harmonized standards, coordinated investments, and policy cohesion, thereby significantly influencing infrastructure development, stakeholder coordination, and market readiness, which ultimately forms the foundation for sustainable green shipping practices. Availability of alternative fuel networks is a vital independent variable for point-to-point green shipping corridors, and is recognised as a critical bottleneck due to the early development stage of ammonia and hydrogen bunkering infrastructure [Jesus et al. 2024], which faces significant cost and regulatory uncertainties, with such proposed solutions as mobile floating bunkering terminals aimed at mitigating these gaps. As an independent driver, the establishment of robust alternative fuel networks influences regulatory support, cost competitiveness, and overall system adoption, thereby laying the foundation for the transition to low-emission fuels and sustainable maritime logistics. High initial investment costs substantially impede point-to-point green shipping corridor development, as adopting innovative technologies demands significant upfront capital that challenges port infrastructure [Ismail et al. 2024]. Traditional banks often refrain from funding these initiatives due to profitability uncertainties, making alternative financing, such as public-private partnerships and green financing, essential to overcome these financial barriers.

One common question is whether traditional fuel-powered vessels will still be permitted in green shipping corridors and, if not, whether rerouting might inadvertently lead to higher overall GHG emissions [Lister, Poulsen and Ponte 2015; Wang, Cheng and Zhen 2023]. In most proposed green shipping corridor initiatives, outright bans on conventional vessels are uncommon; instead, there is a strong emphasis on incentivizing the use of low- and zero-emission technologies, such as dual fuel engine systems and waste-heat recovery systems [Acciaro 2014a, b]. Even in cases where certain vessels may be discouraged or restricted, the potential for increased emissions elsewhere is likely mitigated by the ongoing improvement of alternative fuel infrastructure and the introduction of economic measures (e.g., carbon pricing, bunker levies, cap-and-trade) [Christodoulou and Cullinane 2021]. Over time, these initiatives could make cleaner fuels more competitive and guide the industry toward genuinely lower emissions, rather than simply displacing them to other routes [Yuen et al. 2019].

6. CONCLUSIONS

Point-to-point green shipping corridors refer to designated maritime routes that enable zero-emission shipping operations through the utilization of alternative fuels and sustainable practices between two ports. These corridors are currently in the initiation phase, the first of four sequential stages. The main elements of the initation phase include: (1) formation of a core consortium of stakeholders; (2) alignment on a unified sustainability vision; (3) selection of targeted shipping routes; and (4) evaluation of barriers to corridor establishment. A detailed literature review identified seven critical factors necessary for the strategic development of point-to-point green shipping corridors: (1) High Initital Investment Costs; (2) Availability of Alternative Fuel Networks; (3) Alignment of Regulatory and Political Frameworks; (4) Technological standardization and interoperability; (5) Development of Infrastructure Capacities; (6) Stakeholder Coordination; and (7) Stable Market Demand.

To systematically categorize these factors, Interpretive Structural Modeling (ISM) in conjunction with MICMAC analysis was employed. ISM delineated the interrelationships among the factors, while MICMAC analysis facilitated their classification based on respective driving and dependence powers.

Significant funding is crucial to initiate sustainable maritime infrastructure effectively, driving alternative fuel network development. Consistent alternative fuel supply ensures corridor operational reliability, influenced by investment and driving policy alignment. Harmonized regulations foster streamlined governance, enabling technological standardization and stakeholder coordination. Standard technologies ensure seamless operations, supported by regulatory alignment and facilitating infrastructure growth. Robust port infrastructure supports alternative fuel handling, dependent on technological advancements and regulatory frameworks. Effective collaboration among stakeholders enhances corridor management, driven by aligned regulations and infrastructure readiness. Sustained demand ensures economic viability, reliant on stakeholder efforts, infrastructure capacities, and fuel network availability.

The research outcome is a framework demonstrating how key factors, such as high initial investment costs, availability of alternative fuel networks, and stakeholder coordination, shape point-to-point green shipping corridor implementation, revealing pathways for effective intervention and implementation. These insights enable policymakers, port authorities, and industry stakeholders to plan, implement, and refine point-to-point green shipping corridors, thereby advancing sustainable maritime transport.

Overall, this study offers a framework for strategic development that balances the economic, regulatory, and technological considerations to achieve sustainable maritime transport. The interdependencies highlight the need for integrated planning, where improvements in one area can drive positive outcomes across the system. Future research should explore the long-term impact of implemented corridors to refine strategic approaches further.

ISM and MICMAC are qualitative methodologies that aid in understanding complex relationships; however, this qualitative nature represents a limitation. Future research should address this with further integrative studies validating the proposed model using quantitative approaches, such as Structural Equation

Modeling (SEM) for statistical validation and Bayesian Belief Networks (BBN) for probabilistic reasoning and decision analysis.

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