Energy Policy 214 (2026) 115259

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Transitioning the European maritime industry to hydrogen: a system's perspective for policy making

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ARTICLE INFO

Keywords:
Maritime industry
Sustainable alternative fuels
Hydrogen
Value chain
Adoption
Transition
Policy makers
DEMATEL

ABSTRACT

The adoption of sustainable fuels can support the decarbonization of the maritime industry. This transition requires aligned changes across four interdependent value chains: fuel, shipbuilding, infrastructure, and operations. Even though literature has investigated the relationships among value chain processes, a comprehensive model is missing. This study follows Complex Adaptive Systems (CAS) theory to discuss the effects of sustainable fuel adoption on the processes of the four maritime value chains, considering their interdependencies. A DEMATEL study was conducted involving 12 professionals from various areas of expertise to determine the intensity and directionality of relationships. The results outline dominant cause-and-effect relationships within the system and describe the many cascade effects of alternative fuels adoption. Specifically, the case of hydrogen is explored by considering its unique characteristics. Findings assist policy makers and industry stakeholders by clarifying the maritime system's dynamics, offering directions to accelerate the parallel development of the four maritime value chains, and informing the distribution of resources amongst them. Early in the transition, policy should focus on those identified as the system's drivers. Priorities include securing “green” fuel sources and managing fuel choice complexity. Local port authorities and infrastructure developers become crucial. Investments in storage and bunkering facilities at existing ports attract shipowners early adopters. Policy should promote targeted investments, coordinate the definition of standards, and direct the system's transition with an informed view of the maritime industry as a system-of-systems.

1. Introduction

The maritime industry is experiencing increasing pressure to decrease its environmental impact. The industry significantly contributes to air pollution and climate change, accounting for 2-4% of worldwide carbon dioxide emissions, 10-20% of nitrogen oxides, and 4-8% of sulphur oxides (El Gohary and Seddiek, 2013). In response, the International Maritime Organization (IMO) has established decarbonization targets, aiming to achieve net-zero greenhouse gas (GHG) emissions by 2050 (IMO, 2023). These objectives are consistent with other international initiatives, such as the United Nations' Agenda 2030, Sustainable Development Goal (SDG) 7 on clean and affordable energy, and SDG 14 on the sustainable use of oceans, seas, and marine resources (UN DESA, 2024).

In Europe, a number of strategic policies and regulatory tools are in place to support reaching the overarching sustainability goals. IMO indicators such as the Energy Efficiency Design Index (EEXI) and Carbon Intensity Indicator (CII) are important tools for ships' GHG emissions monitoring and mitigation (Capros et al., 2019). However, reducing fuel consumption alone will not be sufficient, and the 2020 EU Hydrogen Strategy has identified hydrogen as a priority for achieving climate neutrality. In parallel, the REPowerEU plan wishes to reduce Europe's energy dependence by promoting the deployment of infrastructure and hydrogen production plants (Ah-Voun et al., 2024). Together, these policies represent a rapidly changing external environment to which the maritime industry must adapt.

While hydrogen and other hydrogen-derived synthetic fuels (e.g., ammonia, methanol) represent promising pathways to carbon reduction (Mäkitie et al., 2022), fuel cells and internal combustion engines are not yet mature in the industry (i.e., at low or medium technology readiness levels) (Nepomuceno de Oliveira et al., 2022). Their diffusion depends, among others, on the development of policies that support investments (Capros et al., 2019) in technology and infrastructure, and provide subsidies, while easing approval procedures (Bolz et al., 2024). How to

This article is part of a special issue entitled: Policies for Hydrogen published in Energy Policy.

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https://doi.org/10.1016/j.enpol.2026.115259
Received 30 July 2025; Received in revised form 3 February 2026; Accepted 12 March 2026
Available online 17 March 2026

design such policies is a key question (Farrell et al., 2003). In fact, the large-scale adoption of hydrogen requires simultaneous changes to the fuel, shipbuilding, infrastructure, and operations value chains (Bianchi et al., 2025). These value chains are interdependent and must be aligned (Nordic West Office, 2022).

Literature has investigated how specific decisions in one value chain process affect others while cross-chain studies remain scarce (Bianchi et al., 2024). Previous research has explored techno-economic elements of fuel production, storage, and bunkering (Mäkitie et al., 2022), (Usman, 2022). Ship design has focused on intra-chain interdependencies by assessing fuel system alternatives (van Veldhuizen et al., 2023), (Kolodziejski, 2023), (Benet et al., 2022), (Sarı et al., 2021). Port operations and fuel transportation logistics have been evaluated together (Aneziris et al., 2023), (Wang et al., 2021). Previous studies have examined pairwise connections such as fuel choice on ship design (Sürer and Arat, 2022) or port infrastructure layout on operations (Semchukova et al., 2025). However, there is no comprehensive model that considers all four value chains at a time (Bianchi et al., 2024). To fill this gap, we adopt the theory of Complex Adaptive Systems (CAS) (Bale et al., 2015), viewing the maritime industry as a system-of-systems where local interventions can lead to emergent behaviours. The study focuses on the cascade effects of sustainable fuels adoption, which are relevant to all four value chains, either directly or indirectly. The goal is to inform policy by identifying strategic nodes, ordering subsystems for intervention, and proposing ways to coordinate policies across value chains. Ensuring this alignment throughout the fuel transition is critical to the successful adoption of the new fuel (Nordic West Office, 2022). The mere availability of the fuel is insufficient if corresponding ship and infrastructure capabilities are not in place. Therefore, a model that accounts for the interdependencies between value chains and the cross-chain impact of decisions may serve as a valuable instrument in the formulation of effective policies.

To this aim, the study addresses the following research question:

RQ1 – Which interdependencies exist between the processes of the maritime value chains?

RQ2 – What are the implications of the adoption of sustainable alternative fuels on the processes of the maritime value chains, considering their interdependencies?

We define the value chain as the complete set of processes required to bring a product or service from conception, through the numerous phases of production, delivery to end consumers, and final disposal after use (Kaplinsky and Morris, 2001).

To explore the systemic challenges and interdependencies in the maritime industry, the study seeks to gather the perspectives of domain experts across the four maritime value chains. By capturing these expert insights through a DEMATEL (Decision Making Trial and Evaluation Laboratory) analysis (van Veldhuizen et al., 2023) and combining them with findings from the scientific literature, the study is intended to inform policy makers and industry stakeholders, providing practical directions to accelerate the parallel development of the four maritime value chains, with a focus on hydrogen.

The remainder of the paper is organized as follows: Section 2 presents the theoretical background of the research, Section 3 details the DEMATEL methodology, and Section 4 reports the results of the analysis. Finally, Section 5 discusses the findings and policy implications, and Section 6 concludes the paper.

2. Background

2.1. Complex adaptive systems theory

The CAS theory supports the analysis and interpretation of the dynamics of complex socio-technical systems (Bucchiarone, 2019). CAS consists of subsystems and autonomous agents that interact via local logics, resulting in emergent behaviours that cannot be predicted by individual components (Bale et al., 2015). The global energy sector is a dynamic, complex system influenced by both individual components and emergent behaviour from interactions with the changing external environment (Bale et al., 2015). CAS are dynamic due to constant change and interconnected feedback mechanisms (Dueñas Santana et al., 2024). Changes in one system component can lead to many cascade effects, with amplifying or dampening results. These are essential for understanding system interdependencies, considering their dynamic evolution (Dueñas Santana et al., 2024). Individual system components continuously interact across space, time, and social organization (Pearson and Bardsley, 2022). The subsystems adapt to internal or external changes. The components' capabilities and decision rules evolve in these subsystems (Dueñas Santana et al., 2024). In energy transitions, systems and subsystems display high complexity resulting from the many social, political, and physical processes, and the diversity of actors involved (Bale et al., 2015). The resulting cause-and-effect relationships may display nonlinear effects (Pearson and Bardsley, 2022).

2.2. The analysed system: The maritime industry

The maritime industry serves as the system in this study, and its four value chains (i.e., fuel, shipbuilding, infrastructure, and operations) are interdependent and adaptive subsystems. Each of the value chains' processes are individual components managed by autonomous agents, and the policies are representative of the changing external environment. The adoption of hydrogen as a sustainable fuel introduces systemic disruption (Capros et al., 2019), causing structural reorganizations, mutual dependencies, and potential bottlenecks across value chains (Nordic West Office, 2022).

Fig. 1 provides an adaptation of the work by (Nordic West Office, 2022) and illustrates the maritime industry (system), the maritime value chains (subsystems), and their basic interdependencies. Moreover, it shows the processes in each value chain (components).

2.3. Subsystem 1: Fuel value chain

The fuel value chain begins with fuel type selection and progresses through energy sourcing, fuel production, storage, and delivery (Nordic West Office, 2022). The choice of fuel, whether hydrogen, ammonia, methanol, or another alternative, has far-reaching consequences for the system of maritime value chains. It influences the availability, cost, and environmental impact of shipping operations (Bilgili, 2023).

The research on sustainable alternative fuels primarily focuses on fuel characteristics, storage conditions, and distributional challenges (Bianchi et al., 2024). The existing studies outline the trade-offs between alternatives (e.g., liquid or compressed hydrogen, ammonia, methanol) in terms of energy density, storage requirements, and environmental impact (Mäkitie et al., 2022). For instance, ammonia is often favoured for its higher energy density and easier storage compared to compressed hydrogen, but it creates challenges related to toxicity and safety (Valera-Medina et al., 2021). The demanding storage conditions, particularly temperature and pressure, are recurring in the literature (Usman, 2022). The low energy density of hydrogen demands high pressure to be maintained when stored, which increases costs and complicates handling procedures (Usman, 2022). To address these issues, studies propose innovative storage solutions, such as metal hydrides and liquid organic hydrogen carriers (Usman, 2022).

The distribution of emerging fuels to port facilities is another critical area of research (Bianchi et al., 2024). The literature emphasizes the need for strategically placed distribution networks, including pipelines, tankers, and port-based storage facilities. The lack of existing infrastructure for the distribution of any of the sustainable fuels is identified as a significant barrier to adoption (Wulf and Kaltschmitt, 2018).

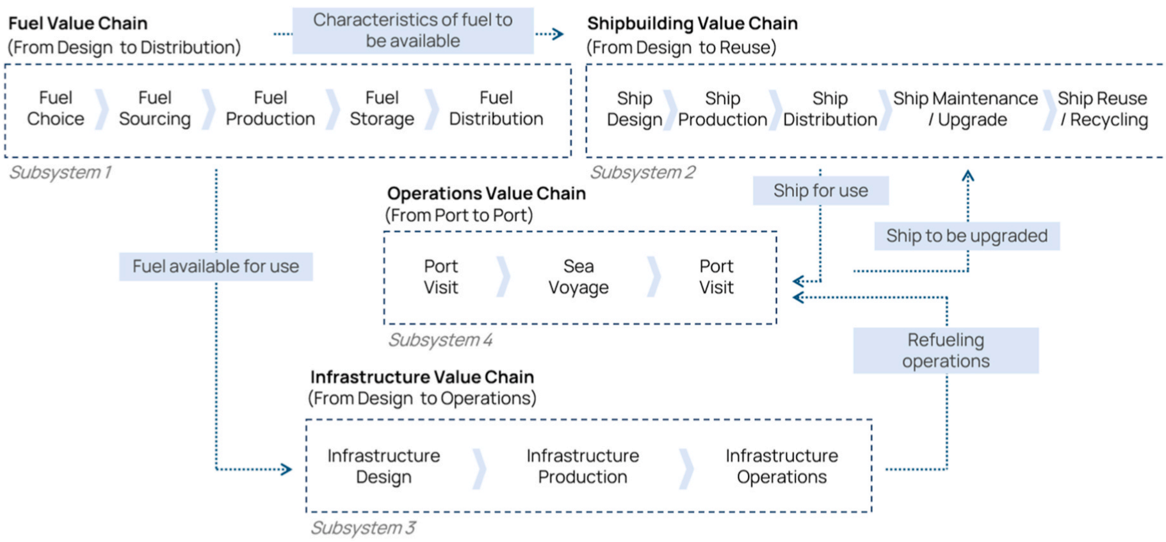

Fig. 1. The maritime industry as a system-of-systems.

2.4. Subsystem 2: Shipbuilding value chain

The shipbuilding value chain comprises ship design, production, delivery, maintenance or upgrade through its use-life, and eventual recycling or disposal (Nordic West Office, 2022). The compatibility of the fuel, the operational range, the capacity of storage, and the operating performance all need to be considered when designing a ship. As the industry moves toward sustainable fuels, shipbuilders must innovate to accommodate new fuel systems and storage solutions onboard (van Veldhuizen et al., 2023). This includes retrofitting existing vessels and designing new ships supporting hydrogen fuel systems.

The research on shipbuilding focuses on the integration of sustainable fuel systems into solutions that have been in place and virtually unchanged for a long time. The design of the ship is central to the literature, with studies exploring the compatibility of different propulsion systems (e.g., fuel cells, internal combustion engines) with hydrogen-derived fuels (Kolodziejski, 2023). In particular, the Proton Exchange Membrane Fuel Cells (PEMFCs) are frequent highlights for their size and efficiency, but their slow response to dynamic load changes still represents a limit (Benet et al., 2022).

The retrofitting of existing ships to accommodate new fuels is another area of interest. The few studies that are present in the literature propose modifications and upgrades, as well as the possibility of introducing hydrogen as an auxiliary power source (Sarı et al., 2021). However, retrofitting is often hindered by the limited space onboard and the high costs. The research on ship reuse or recycling and disposal at the end-of-life is limited, reflecting a gap in the literature (Bianchi et al., 2024).

2.5. Subsystem 3: Infrastructure value chain

The infrastructure value chain includes the design, production, and operations of ports (Nordic West Office, 2022). The current infrastructure must be adapted to the distribution of the new fuels, first by integrating refuelling solutions into the design of the port, then necessitating significant investments in new technology, and, finally, conducting operations with an attention to safety measures. Safety considerations and consequences assessments have been carried out by comparing the toxicity of ammonia and the flammability of hydrogen (Aneziris et al., 2023).

In the literature, the infrastructure value chain is among the least studied areas (Bianchi et al., 2024). The studies highlight the lack of standards and regulations for hydrogen handling at ports, which places port operators at risk (Wang et al., 2021). Only a few studies concentrate on the configuration of bunkering facilities (Lukauskas, 2025). However, the research on fuel storage suggests that high-pressure refuelling systems and cryogenic storage tanks will be required, leading to significant consequences in the operational costs and safety of infrastructure. In particular, the studies outline the need for coordinated investments to render sustainable sea voyages feasible (Semchukova et al., 2025).

2.6. Subsystem 4: Operations value chain

The maritime operations value chain is cyclical, as it alternates sea voyages (i.e., navigation) and port visits (i.e., docking) (Nordic West Office, 2022). The operations value chain connects the other three subsystems (i.e., fuel, shipbuilding, and infrastructure), making it central to the system (as seen in Fig. 1). The design of the ship and its operational performance (Benet et al., 2022), the availability of a compatible fuel along the route (Inal, 2024), and the infrastructural readiness to deliver it (Chen et al., 2023) are all factors that influence maritime operations. For instance, using hydrogen as a fuel may require larger storage tanks and, as a result, longer refuelling times, affecting route planning and cargo capacity (Aneziris et al., 2023), (Van Hoecke et al., 2021).

The operational characteristics of hydrogen-powered ships, including the cruising range and the refuelling frequency, are important variables. Oftentimes, the introduction of sustainable fuels resulted in larger storage tanks due to their inner properties, reducing cargo capacity and increasing voyage costs. In the literature, the longer refuelling times and the specialized handling procedures are seen as a limit. These changes can challenge port schedules and increase operational costs (Sürer and Arat, 2022), (Lukauskas, 2025). The research emphasizes the importance of safety protocols for the storage, handling, and refuelling of fuels. This goes hand in hand with the need for upskilling of personnel, onboard vessels, as well as at ports (Prussi et al., 2021).

3. Methodology

3.1. DEMATEL method

Although research acknowledges several connections across maritime value chains, an overarching understanding of the cause-and-effect relationships among their processes is missing (Bianchi et al., 2024). This prevents a comprehensive understanding of the dynamics of sustainable fuel adoption across the industry. Thus, we sought a method for empirically capturing the direction and intensity of interdependencies among value chain processes. This was accomplished using the DEMATEL method (Falatoonitoosi et al., 2013).

After considering different multi-criteria decision-making (MCDM) methods such as the analytic hierarchy process (AHP), grey relational analysis (GRA), technique for order of preference by similarity to ideal solution (TOPSIS), and elimination and choice expressing reality (ELECTRE), the DEMATEL method was chosen. Several advantages differentiate DEMATEL from other MCDM approaches (Si et al., 2018), (Alinezhad and Khalili, 2019). First, DEMATEL evaluates direct and indirect effects of numerous components and helps understand the complex cause-and-effect relationships in the decision-making dilemma. Second, DEMATEL uses an influence relation map to show decision-makers (i.e., policy-makers in this research's scenario) how the components are interdependent. Third, DEMATEL can rank components based on their influence inside the system, identify components to be monitored, and support weighing of components for further inquiries. It was demonstrated that DEMATEL is a valuable approach for theorizing when it comes to plenty of research fields (Damavandi et al., 2025), (Lee and Lin, 2013), (Ogrodnik, 2018), including renewable and sustainable energy (Kumar et al., 2017).

DEMATEL is a method for determining cause-and-effect relationships between the components of a complex system. The input of a DEMATEL study consists of matrices to be filled by industry experts. For a typical DEMATEL analysis of this type, where depth of knowledge is prioritized over sample size, a dozen respondents is a reasonably high number (Lee and Lin, 2013).

The final output shows how the components inserted into the matrix interact with one another. DEMATEL helps to categorize components into causes and effects and specify the directionality of their interactions. The DEMATEL approach is consistent with the CAS theoretical approach in that it explicitly identifies systemic interdependencies and categorizes components, i.e., processes, as causes and effects.

3.2. DEMATEL steps

The DEMATEL method follows a structured approach consisting of five key steps (Ogrodnik, 2018): *Step 1 – Computing the direct-relation matrix (X)*, *Step 2 – Computing the normalized direct-relation matrix (N)*, *Step 3 – Computing the total-relation matrix (T)*, *Step 4 – Computing the significance and relation indicators*, and *Step 5 – Drawing the cause-and-effect relationships diagram*.

We chose hydrogen to contextualize the DEMATEL study due to its emergence as a preferred sustainable alternative, as well as the fact that many other alternatives are derivatives of it (e.g., ammonia, methanol) (Ruth and Stephanopoulos, 2023).

The analysis is based on 12 responses collected from a pool of 49 participants at the final event of a European research project (e-SHyIPS, Clean Hydrogen Partnership). The participants were representatives of research institutions, fuel cell developers, port and shipping operators, shipyards, and regulatory bodies who had either taken part in the project or had prior experience with sustainable fuels applications. Indeed, given that the event was open to the public, the participants' attendance at the event does not imply that they have collaborated on specific projects; rather, it reflects their interest in hydrogen technologies. Moreover, each participant completed the questionnaire autonomously and independently. The selection of experts is open to potential bias. While the sample includes representatives from all value chains, the concentration of expertise in specific domains (e.g., fuel or shipbuilding) may result in a more reliable model within these subsystems. On the other side, organizational bias was reduced because no two experts came from the same organization. Geographically, the experts represented 7 European countries: Italy, Greece, Cyprus, Spain, Germany, the Netherlands, and Finland. All of the participants had at least 4 years of experience in the field and an average of 16.7 years of experience. The final sample includes 12 professionals: 3 experts in shipbuilding, 3 in port and infrastructure, 1 in maritime services and operations, 4 in fuel, and 1 did not answer the question on the area of expertise.

Step 1: Computing the direct-relation matrix (X). Each expert completed a matrix assessing the degree of influence of each process on the others across the four maritime value chains.

In the matrix to be filled by experts, 15 components were grouped into four main subsystems, which are *1 – Fuel Value Chain*, *2 – Shipbuilding Value Chain*, *3 – Infrastructure Value Chain*, and *4 – Operations Value Chain*, respectively. The components of Subsystem 1 – *Fuel Value Chain* are: *C1 – Fuel Choice*, *C2 – Fuel Sourcing*, *C3 – Fuel Production*, *C4 – Fuel Storage*, *C5 – Fuel Delivery*. The components of Subsystem 2 – *Shipbuilding Value Chain* are: *C6 – Ship Design*, *C7 – Ship Production*, *C8 – Ship Delivery*, *C9 – Ship Maintenance/Upgrade*, *C10 – Ship Reuse/Recycle*. The components of Subsystem 3 – *Infrastructure Value Chain* are: *C11 - Infrastructure Design*, *C12 - Infrastructure Production*, and *C13 – Infrastructure Operations*. The components of Subsystem 4 – *Operations Value Chain* are: *C14 – Sea Voyage*, and *C15 – Port Visit* (Table 1).

Although this number of components is still accepted in the relevant literature (Ogrodnik, 2018), having so many renders the task of comparing and assessing relationships more difficult for respondents. To validate the task's feasibility, two tests were conducted prior to data collection. Moreover, respondents were given written instructions and a glossary of terms to help clarify and uniquely identify the meaning of each component in the matrix. Each respondent took as much time as needed to fill the matrix. To ensure transparency and reproducibility, the individual expert assessment matrices used to calculate the direct-relation matrix (X) are provided in Appendix C.

We asked each interviewed professional to rate the direct influence of any two processes (e.g., How influential is *C6 – Ship* design on *C13 – Infrastructure operations*?) using the following scale: 0 – "no influence", 1 – "very low influence", 2 – "low influence", 3 – "high influence", and 4 – "very high influence". We refer to the average of the matrices filled by experts as the direct-relation matrix (*X*), which is reported in Formula (1):

$$X = \begin{bmatrix} 0 & x_{12} & \cdots & x_{1n} \\ x_{21} & 0 & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & 0 \end{bmatrix} \tag{1}$$

In the direct-relation matrix, *xij* represents the degree of influence of process *i* over process *j*. The diagonal in the direct-relation matrix is set to zero, indicating that a process does not affect itself. For instance, *C13 – Infrastructure operations* interacts with other processes such as *C6 – Ship*

Table 1
Subsystems and components of the analysis.

Subsystem	Component	Abbreviation
1 – Fuel Value Chain	*Fuel Choice*	C1
	Energy Sourcing	C2
	Fuel Production	C3
	Fuel Storage	C4
	Fuel Delivery	C5
2 – Shipbuilding Value Chain	*Ship Design*	C6
	Ship Production	C7
	Ship Delivery	C8
	Ship Maintenance/Upgrade	C9
	Ship Reuse/Recycle	C10
3 – Infrastructure Value Chain	*Infrastructure Design*	C11
	Infrastructure Production	C12
	Infrastructure Operations	C13
4 – Operations Value Chain	*Sea Voyage*	C14
	Port Visit	C15

design and *C4 – Fuel storage* rather than directly influencing itself within the matrix. The focus is on the interdependencies between various components of the maritime value chains.

Step 2: Computing the normalized direct-relation matrix (N). In this study, normalization is performed by identifying the greatest value in the sum of the rows of the direct-relation matrix. The λ-value is the reciprocal of that value, and it serves as the normalization basis. Formula (2) establishes the normalized direct-relation matrix (*N*).

$$N = \lambda X \tag{2}$$

Step 3: Computing the total-relation matrix (T). Once the normalized direct-relation matrix (*N*) is known, the identity matrix (I) (i.e., a matrix with a diagonal value of 1 and all other values set to 0) is used to compute the total-relation matrix (*T*), as shown in Formula (3).

$$T = N\,(I - N)^{-1} \tag{3}$$

Step 4: Computing the significance and relation indicators. After computing the total-relation matrix, *Ri* is defined as the sum of the rows, which represents the sum of the influence exerted by process *i* on all other processes. *Ci* is defined as the sum of the columns, which represents the sum of the influence received by process *i* from all other processes.

The significance indicator (*Ri* + *Ci*) reveals the total degree of engagement of a process into the system, expressing the strength of its connection to other processes, either by receiving or exerting influence. The relation indicator (*Ri-Ci*) reveals the contribution of a process as either a cause or an effect within the system.

Step 5: Drawing the cause-and-effect relationships diagram. The cause-and-effect relationships diagram is constructed by plotting the values of *Ri* + *Ci* and *Ri-Ci* for each process. The cause-and-effect relationships diagram simplifies complex relations between processes by demonstrating how each affects the others. This diagram shows the significance indicator (*Ri* + *Ci*) as the horizontal axis and the relation indicator (*Ri-Ci*) as the vertical axis. The diagram permits interpretation of the degree of influence and directionality of each process. A process with a high significance indicator (*Ri* + *Ci*) has a significant influence within the system compared to others. A process with a relation indicator (*Ri-Ci*) above zero contributes as a cause rather than an effect towards the equilibrium of the system. Essentially, if a process is placed to the right of the diagram, it has a stronger presence, and a process located above the *x*-axis has more effect on others.

3.3. Sensitivity analysis

To assess the robustness of the findings derived from the total-relation matrix (*X*), a sensitivity analysis is performed. The results of the sensitivity analysis are reported in *Annex B*. Initially, the standard deviation of expert-based scoring, as well as the consensus on each relationship, is explored (*Annex A*). Clear methodological references were considered when performing the analysis, and the effect of changes in the evaluation of components by experts was assessed on the ranking result (Demir et al., 2024), (Mukhametzyanov and Pamučar, 2018). The input data, which is the total-relation matrix (*X*), was randomly distributed around the values of standard deviation using formula (4) below:

$$x'_{i,j} = x_{i,j} + (2^{*}\xi - 1)^{*}\,\sigma_{i,j} \tag{4}$$

where:

- $x_{i,g}$: the original value in the total-relation matrix (*X*)
- $x'_{i,g}$: the perturbed value in the new total-relation matrix (*X'*)
- ξ: a random variable uniformly distributed between 0 and 1.
- $\sigma_{i,j}$: the value of the standard deviation for $x_{i,g}$.

The formula is structured in such a way that the perturbed values in the new total-relation matrix (*X'*) fall within the interval $x_{i,j} \pm \sigma_{i,j}$. Each matrix element is perturbed randomly within the boundaries of the standard deviation from its original value.

The ranking of influence (i.e., the sum of the rows of each component) and its variations from the initial run were then used to assess the results (Demir et al., 2024). A total of 20 runs were executed consecutively.

4. Results

4.1. Direct-relation matrix (X)

The average of the scores provided by the 12 experts is reported in Table 2, and it represents the initial direct-relation matrix (*X*).

4.2. Normalized direct-relation matrix (N)

The highest value in the direct-relation matrix, as determined by the sum of the rows, was 39.20, which was found in row C1. The reciprocal of this value (λ) was used as the normalization basis. The normalized direct-relation matrix (*N*) is shown in Table 3.

4.3. Total-relation matrix (T)

Finally, the total-relation matrix (*T*) was computed by using the normalized relation matrix (*N*) and (*I* - *N*)-1, according to formula *T* = (*I* - *N*)-1, and the results are shown in Table 4.

4.4. Significance and relation indicators and the cause-and-effect relationships diagram

Each component's systemic role depends on the significance (*Ri* + *Ci)* and relation (*Ri-Ci)* indicators. Based on *Ri* and *Ci*, we identify the characteristics of each process (Table 5).

The significance indicator (*Ri* + *Ci*) determines a component's overall involvement in the system: the higher the significance indicator, the greater the involvement. For example, *C1 – Fuel Choice* has the highest engagement within the system (*Ri* + *Ci* = 7.13), while *C8 – Ship Delivery* has the lowest (*Ri* + *Ci* = 3.00). The takeaway is that *C1 – Fuel Choice* is considered alongside a variety of other process decisions, either influencing or being influenced, whereas *C8 – Ship Delivery* is considered separately from the vast majority of them.

The relation indicator (*Ri-Ci*) specifies a component's causal role: a positive value classifies a net cause, while a negative value classifies a net effect. A net cause is a component that exerts more influence on other components than it receives. Conversely, a net effect receives more influence than it exerts. For example, *C2 – Fuel Sourcing* is a strong driver (*Ri-Ci* = 0.24). *C2 – Fuel Sourcing* is highly influential because it determines whether the system is sustainable or not (Shi et al., 2023). Even common hydrogen nomenclature (e.g., green from renewable sources, yellow from grid electricity from various sources) is dependent on it (Weiβensteiner, 2025). *C9 – Ship Maintenance/Upgrade* is a clear net effect (*Ri-Ci* = −0.29) indicating scarce interest in hydrogen-powered ship's end-of-life. The values of the significance (*Ri* + *Ci*) and relation (*Ri*−*Ci*) indicators for each component are reported in Table 5.

The quadrants of the cause-and-effect relationship diagram (Fig. 2) are named in line with (Qin et al., 2024). The quadrants are defined horizontally by the x-axis and vertically by an axis halfway between the minimum and maximum values of *Ri* + *Ci* (x = 5.07). The upper-left

Table 2
Initial direct-relation matrix (*X*).

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
C1	0.00	3.25	3.25	3.92	3.67	3.08	2.00	1.08	2.50	2.08	3.50	3.08	3.08	2.00	2.67
C2	3.42	0.00	2.83	2.75	2.67	1.75	1.42	0.75	1.58	1.25	2.50	2.42	2.50	1.67	1.33
C3	3.00	3.00	0.00	2.25	2.58	0.92	0.58	0.42	0.75	0.67	2.67	2.42	2.17	0.67	0.83
C4	3.75	2.25	2.00	0.00	3.25	3.00	2.33	1.00	2.17	1.58	2.58	2.17	2.58	2.00	2.00
C5	3.67	2.42	2.83	3.25	0.00	1.75	1.17	0.50	1.17	1.17	3.42	2.75	3.00	2.25	2.50
C6	2.83	1.83	1.00	2.83	1.75	0.00	3.42	2.67	3.42	3.50	2.25	1.58	2.00	2.75	2.42
C7	2.08	1.50	0.83	1.92	1.17	3.08	0.00	2.17	2.75	2.75	1.25	1.00	1.17	1.58	1.25
C8	1.00	0.50	0.50	0.67	0.50	2.33	2.33	0.00	1.75	1.75	1.00	0.83	0.83	1.25	0.75
C9	1.92	0.83	0.67	1.08	0.67	3.00	2.58	1.50	0.00	2.83	1.33	0.92	1.50	2.17	1.58
C10	1.67	1.08	0.58	1.25	0.92	3.08	2.25	1.67	2.75	0.00	0.83	0.83	0.58	1.08	0.83
C11	3.42	2.17	2.83	3.00	3.50	2.08	1.25	0.67	1.17	0.92	0.00	3.08	3.25	1.92	2.83
C12	2.92	1.92	2.42	2.58	2.67	1.25	0.83	0.75	0.92	0.67	3.33	0.00	3.17	1.33	2.00
C13	2.92	2.25	2.50	2.92	3.42	2.00	1.00	0.92	1.50	0.83	3.33	3.17	0.00	2.00	2.75
C14	2.75	2.08	1.00	2.25	2.50	3.00	1.67	1.50	1.92	1.00	1.50	1.33	2.00	0.00	2.08
C15	2.25	1.25	0.83	1.92	2.17	2.33	1.08	1.00	1.25	0.83	2.42	1.83	2.25	2.08	0.00

Table 3
Normalized direct-relation matrix (*N*).

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
C1	0.00	0.08	0.08	0.10	0.09	0.08	0.05	0.03	0.06	0.05	0.09	0.08	0.08	0.05	0.07
C2	0.09	0.00	0.07	0.07	0.07	0.04	0.04	0.02	0.04	0.03	0.06	0.06	0.06	0.04	0.03
C3	0.08	0.08	0.00	0.06	0.07	0.02	0.01	0.01	0.02	0.02	0.07	0.06	0.06	0.02	0.02
C4	0.10	0.06	0.05	0.00	0.08	0.08	0.06	0.03	0.06	0.04	0.07	0.06	0.07	0.05	0.05
C5	0.09	0.06	0.07	0.08	0.00	0.04	0.03	0.01	0.03	0.03	0.09	0.07	0.08	0.06	0.06
C6	0.07	0.05	0.03	0.07	0.04	0.00	0.09	0.07	0.09	0.09	0.06	0.04	0.05	0.07	0.06
C7	0.05	0.04	0.02	0.05	0.03	0.08	0.00	0.06	0.07	0.07	0.03	0.03	0.03	0.04	0.03
C8	0.03	0.01	0.01	0.02	0.01	0.06	0.06	0.00	0.04	0.04	0.03	0.02	0.02	0.03	0.02
C9	0.05	0.02	0.02	0.03	0.02	0.08	0.07	0.04	0.00	0.07	0.03	0.02	0.04	0.06	0.04
C10	0.04	0.03	0.01	0.03	0.02	0.08	0.06	0.04	0.07	0.00	0.02	0.02	0.01	0.03	0.02
C11	0.09	0.06	0.07	0.08	0.09	0.05	0.03	0.02	0.03	0.02	0.00	0.08	0.08	0.05	0.07
C12	0.07	0.05	0.06	0.07	0.07	0.03	0.02	0.02	0.02	0.02	0.09	0.00	0.08	0.03	0.05
C13	0.07	0.06	0.06	0.07	0.09	0.05	0.03	0.02	0.04	0.02	0.09	0.08	0.00	0.05	0.07
C14	0.07	0.05	0.03	0.06	0.06	0.08	0.04	0.04	0.05	0.03	0.04	0.03	0.05	0.00	0.05
C15	0.06	0.03	0.02	0.05	0.06	0.06	0.03	0.03	0.03	0.02	0.06	0.05	0.06	0.05	0.00

Table 4
Total-relation matrix (*T*), with stronger relationships shown in red and weaker relationships in blue.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
C1		0.25	0.24	0.31	0.30	0.28	0.20	0.13	0.22	0.19	0.30	0.26	0.27	0.21	0.24
C2	0.27		0.20	0.23	0.23	0.20	0.15	0.10	0.16	0.13	0.22	0.20	0.21	0.16	0.17
C3	0.23	0.19		0.19	0.20	0.15	0.11	0.07	0.12	0.10	0.20	0.18	0.18	0.12	0.13
C4	0.29	0.20	0.19		0.26	0.24	0.18	0.11	0.19	0.16	0.24	0.21	0.23	0.19	0.20
C5	0.29	0.21	0.21	0.26		0.21	0.15	0.10	0.16	0.14	0.26	0.22	0.24	0.19	0.21
C6	0.27	0.19	0.16	0.24	0.21		0.21	0.16	0.22	0.20	0.23	0.19	0.21	0.20	0.20
C7	0.20	0.14	0.12	0.18	0.15	0.20		0.12	0.17	0.16	0.16	0.13	0.15	0.14	0.14
C8	0.12	0.08	0.07	0.10	0.09	0.14	0.12		0.11	0.10	0.11	0.09	0.10	0.10	0.09
C9	0.18	0.12	0.10	0.15	0.13	0.19	0.15	0.10		0.15	0.15	0.12	0.15	0.14	0.14
C10	0.16	0.11	0.09	0.13	0.12	0.18	0.13	0.10	0.15		0.12	0.11	0.11	0.11	0.10
C11	0.29	0.20	0.21	0.26	0.26	0.22	0.16	0.10	0.16	0.14		0.23	0.25	0.18	0.22
C12	0.25	0.18	0.18	0.22	0.22	0.17	0.13	0.09	0.14	0.11	0.23		0.22	0.15	0.17
C13	0.27	0.20	0.20	0.25	0.26	0.21	0.15	0.11	0.17	0.13	0.26	0.23		0.18	0.21
C14	0.23	0.17	0.14	0.20	0.20	0.21	0.15	0.11	0.16	0.12	0.18	0.16	0.19		0.17
C15	0.21	0.14	0.13	0.18	0.18	0.18	0.12	0.09	0.13	0.11	0.19	0.16	0.18	0.15	

quadrant consists of driving factors with a causal influence ($Ri\text{-}Ci > 0$) but low prominence ($Ri + Ci < 5.07$). The upper-right quadrant comprises the core elements, which are also driving factors ($Ri\text{-}Ci > 0$) but have a high system prominence ($Ri + Ci > 5.07$). The independent factors are identified in the lower-left quadrant, which suggests they are fairly isolated. The components in this quadrant have low prominence ($Ri + Ci < 5.07$), therefore they are rarely engaged in the system. When they are, they are primarily driven by others without exerting influence themselves ($Ri\text{-}Ci < 0$). The lower-right quadrant shows dependent factors, which are effects driven by others ($Ri\text{-}Ci > 0$) with a high system prominence ($Ri + Ci > 5.07$).

4.5. Causal relations between the four subsystems

An additional matrix was computed based on the average influence exerted by the components of one subsystem on the components of

Table 5
Significance (*Ri* + *Ci*) and relation (*Ri*−*Ci*) indicators, along with the identification of each component as a cause or an effect.

Component	*Ri*	*Ci*	*Ri* + *Ci*	*Ri* - *Ci*	Identify
C1 – Fuel Choice	3.64	3.49	7.13	0.14	Cause
C2 – Fuel Sourcing	2.76	2.52	5.28	0.24	Cause
C3 – Fuel Production	2.27	2.35	4.62	−0.08	Effect
C4 – Fuel Storage	3.09	3.10	6.19	0.00	Cause
C5 – Fuel Distribution	3.05	3.00	6.06	0.05	Effect
C6 – Ship Design	3.07	2.97	6.04	0.10	Cause
C7 – Ship Production	2.24	2.21	4.44	0.03	Effect
C8 – Ship Delivery	1.47	1.53	3.00	−0.07	Effect
C9 – Ship Maintenance/Upgrade	2.07	2.36	4.43	−0.29	Effect
C10 – Ship Reuse/Recycle	1.79	2.03	3.82	−0.24	Effect
C11 – Infrastructure Design	3.07	3.03	6.10	0.04	Cause
C12 – Infrastructure Production	2.60	2.63	5.23	−0.03	Cause
C13 – Infrastructure Operations	3.00	2.87	5.87	0.14	Cause
C14 – Sea Voyage	2.52	2.34	4.86	0.19	Cause
C15 – Port Visit	2.27	2.48	4.75	−0.21	Effect

Ri: row sum of the total-relation matrix (T); Ci: column sum of the total-relation matrix (T); Ri + Ci: significance indicator; Ri-Ci: relation indicator.

another subsystem. The outcome demonstrates the extent of influence among the four subsystems (*1 – Fuel Value Chain*, *2 – Shipbuilding Value Chain*, *3 – Infrastructure Value Chain*, *4 – Operations Value Chain*). The resultant matrix was then used to produce a diagram depicting the exchange of influence among subsystems, highlighting connections above average (Fig. 3).

4.6. Sensitivity analysis

The results of the sensitivity analysis are shown in Fig. 4. The outcomes are robust, with influential components repeatedly ranking high and non-influential components ranking low. The "cause" and "effect" components were consistently set apart, demonstrating robustness. Component *C1 – Fuel Choice* was the most influential component throughout iterations. Similarly, component *C8 – Ship Delivery* was the least influential component, except for two outliers. In terms of stability of the ranking, most components display small interquartile ranges and short whiskers, implying low variability. In contrast, components such as *C3 – Fuel Production*, *C4 – Fuel Storage*, and *C7 – Ship Production*, with longer whiskers or larger interquartile ranges, showed medium to high variability between iterations. *C13 – Infrastructure Operations* showed more variability than others. This might be due to its central, mediating role in the system. Its many incoming connections (e.g., from C5, C11, C12) and outgoing influences (e.g., to C14, C15), increase its overall ranking variability. Components such as *C4 – Fuel Storage*, *C5 – Fuel Delivery*, and *C6 – Ship Design* display some overlap, implying that their ranking order varied between iterations. Components *C2 – Fuel Sourcing* and *C14 – Sea Voyage* present outliers across iterations.

Overall, the study is robust because high-influence components were correctly identified and consistently performed in comparison to low-influence ones. The ranking order in the middle of the group may have changed over iterations, but the positions in the quadrants of the cause-and-effect relationships diagram remained largely unaffected. The standard deviation of the final ranking positions is generally low, with an average change of 1.39 positions from the original scenario, reported and commented on in this study, over twenty iterations, where input values from the direct-relation matrix (*X*) had been significantly perturbed.

5. Discussion

5.1. Answer to RQ1 – processes interdependences

Combining the total-relation matrix (*T*) with the significance and relation indicators and their graphical representations, it can be observed that the processes of the maritime value chains are highly interdependent. Indeed, each process of the matrix exerts and receives at least some influence (with relations ranging from a minimum of 0.09 to a maximum of 0.31) from any other process (see Table 4). The most significant interdependencies are described below.

Starting from Subsystem 1 – *Fuel Value Chain, C1 – Fuel Choice* (*Ri* + *Ci* = 7.13, *Ri-Ci* = +0.14) and *C2 – Fuel Sourcing* (*Ri* + *Ci* = 5.28, *Ri-Ci* = +0.24) occupy the upper-right quadrant in the cause-and-effect relationships diagram (Fig. 2). They are core factors, meaning they are driving factors with high prominence in the system. In particular, they exert a strong influence on downstream processes of the same value chain. For instance, *C1 – Fuel Choice* exerts a strong influence on *C4 – Fuel Storage* (C1 → C4: 0.31) and *C5 – Fuel Distribution* (C1 → C5: 0.30) (see Table 4).

The fuel (e.g., hydrogen, ammonia, methanol) and its storage form (e.g., liquid or compressed hydrogen) determine the storage system and its specifications. Liquid hydrogen requires cryogenic tanks but has a

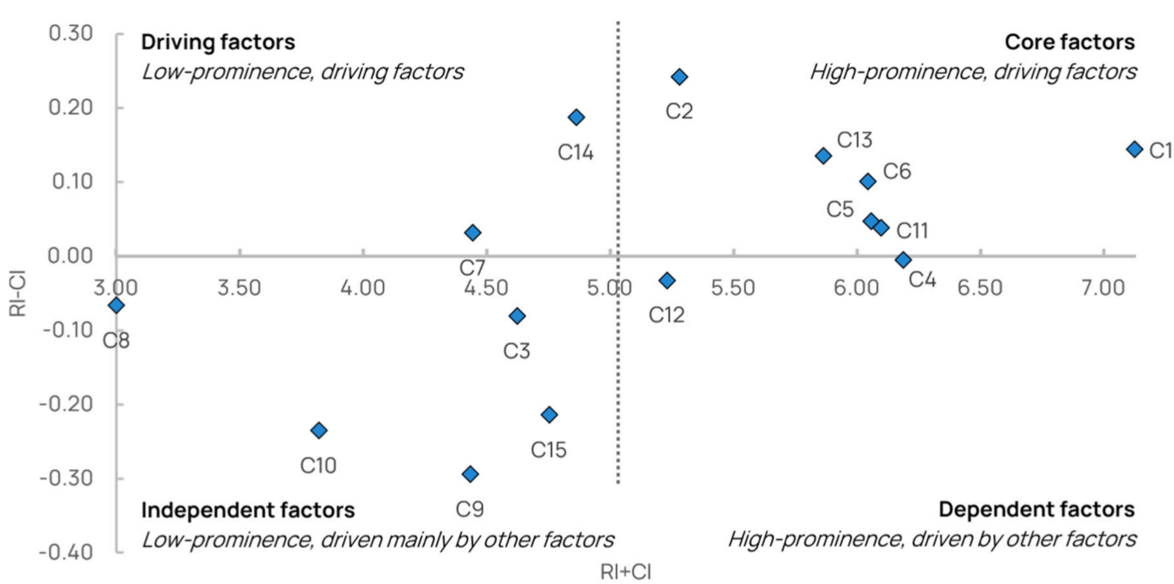

Fig. 2. Cause-and-effect relationships diagram. The horizontal axis indicates the significance indicator (*Ri* + *Ci*), while the vertical axis indicates the relationship indicator (*Ri-Ci*).

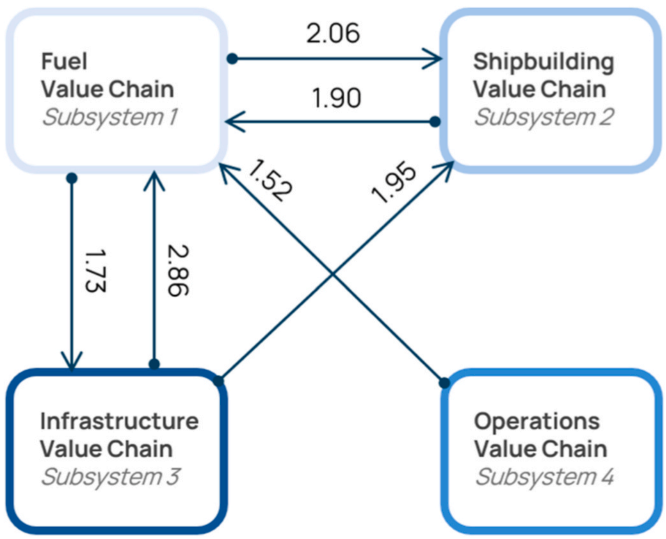

Fig. 3. Subsystems' (fuel, shipbuilding, infrastructure, and operations value chains) interdependencies.

higher volumetric energy density than compressed hydrogen, requiring larger storage volumes (Raucci et al.). *C1 – Fuel Choice* also significantly affects *C6 – Ship Design* (C1 → C6: 0.28), connecting Subsystem 1 – *Fuel Value Chain* and Subsystem 2 – *Shipbuilding Value Chain* (S1 → S2: 2.06). This confirms the literature: the choice of the fuel strongly interferes with the layout of the ship, its weight, and its operational performance (Xing et al., 2021).

C3 – Fuel Production (*Ri* + *Ci* = 4.62, *Ri-Ci* = −0.08) stands in the lower-left quadrant in the cause-and-effect relationships diagram. It is an independent factor whose involvement in the system is limited to its own value chain's sequential connections (e.g., C3 → C4: 0.19). Other than that, it is mutually dependent on *C1 – Fuel Choice* (C1 → C3: 0.24; C3 → C1: 0.23). The selected fuel determines the associated production pathway, and the other way around (e.g., blue hydrogen is produced from steam reforming with carbon capture) (Atilhan et al., 2021).

C4 – Fuel Storage (*Ri* + *Ci* = 6.19, *Ri-Ci* = 0.00) is a perfectly balanced component in the system, resting on the x-axis. In line with the literature, the storage solution is dictated by the characteristics of the chosen fuel (C1 → C4: 0.31) and its need for specific temperature and pressure to be maintained (Brouzas et al., 2025). However, it is then responsible for influencing storage infrastructure at ports (C4 → C13: 0.23) and onboard ships (C4 → C6: 0.24) (Lukauskas, 2025), (Durbin and Malardier-Jugroot, 2013). In practical terms, for a Panamax container ship, 350 bar compressed hydrogen requires more than twice the storage volume of liquid hydrogen to achieve the same operating range, reducing cargo space (Raucci et al.).

C5 – Fuel Distribution (*Ri* + *Ci* = 6.06, *Ri-Ci* = 0.05) acts as a mediator, connecting *C2 – Fuel sourcing* (C2 → C5: 0.23) and *C3 – Fuel production* (C4 → C5: 0.26) to end-users through *C13 – Infrastructure Operations* (C5 → C13: 0.24).

In Subsystem 2 – *Shipbuilding Value Chain, C6 – Ship Design* (*Ri* + *Ci* = 6.04, *Ri-Ci* = +0.10) occupies the upper-right quadrant of the cause-and-effect relationships diagram (Fig. 2). This is a core factor, which means it has a significant causal influence on the system. While heavily influenced by *C1 – Fuel Choice* (C1 → C6: 0.28), it also has a significant influence on other processes, including *C9 – Ship Maintenance/Upgrade* (C6 → C9: 0.22). In particular, as shown in the literature, integrating hydrogen fuel systems into ship design with existing storage solutions is a significant challenge (Usman, 2022), (Lukauskas, 2025).

C9 – Ship Maintenance/Upgrade (*Ri* + *Ci* = 4.43, *Ri-Ci* = −0.29) is a net effect factor, as shown by its positioning in the lower-left quadrant of the cause-and-effect relationships diagram. The component is classified as an independent factor because it exerts low influence in the system (see Table 4). However, such an extreme positioning is not ideal from a strategic viewpoint, considering the potential value of retrofitting efforts (Soni et al., 2023). The retrofitting of existing fleets could prove environmentally and economically advantageous for shipowners, considering the lifespan of certain ships, in meeting new regulations. Furthermore, the need for specialized maintenance procedures for hydrogen-powered ships is an emerging matter, too (Prussi et al., 2021).

C10 – Ship Reuse/Recycling (*Ri* + *Ci* = 3.82, *Ri-Ci* = −0.24) is another independent factor, reflecting its limited impact on the planning phases of its corresponding value chain (e.g., C10 → C6: 0.18). However, it may gain prominence as hydrogen-powered ships start to reach the end of their lifecycle (Dong et al., 2024).

In Subsystem 3 – *Infrastructure Value Chain, C11 – Infrastructure Design* (*Ri* + *Ci* = 6.10, *Ri-Ci* = +0.04) and *C13 – Infrastructure Operations* (*Ri* + *Ci* = 5.87, *Ri-Ci* = +0.14) are core factors, highly influential, reflecting the need for hydrogen-compatible solutions at ports (Leo et al., 2010) and their smooth functioning (Semchukova et al., 2025). The early investment in bunkering facilities and storage solutions is a driver in shaping the behaviour of the system (Hoang et al., 2023).

In Subsystem 4 – *Operations Value Chain, C14 – Sea Voyage* (*Ri* + *Ci* = 4.86, *Ri-Ci* = +0.19) is a driving factor, reflecting the centrality of operational requirements for hydrogen-powered ships. As previously seen in the literature, the need for longer cruising ranges and smaller storage solutions are two directions to pursue. *C15 – Port Visit* (*Ri* + *Ci* = 4.75, *Ri-Ci* = −0.21) is an independent factor, lightly influenced by upstream decisions related to *C6 – Ship Design* (C6 → C15 relation: 0.20) and all aspects of infrastructure (i.e., C11, C12, C13).

Some of the relationships identified may have nonlinear effects. For example, *C1 – Fuel Choice* and *C2 – Fuel Sourcing* have significant influence on downstream processes. However, it is reasonable to expect that only a significant increase in the adoption of green hydrogen is likely to cause significant changes in the system through the cascading effects outlined so far. Similarly, *C6 – Ship Design* and *C13 – Infrastructure Operations* are shown as mutually dependent (C6 → C13: 0.21; C13 → C6: 0.21). However, they could be tied by a nonlinear feedback loop in which significant steps in one constrain or heavily influence the other (e.g., safety requirements in bunkering may dictate the design of specific parts of the ship or its layout). Finally, technological breakthroughs in balanced but central components, such as *C4 – Fuel Storage* (*Ri* + *Ci* = *6.19*), which is highly connected, have the potential to produce large-scale nonlinear effects.

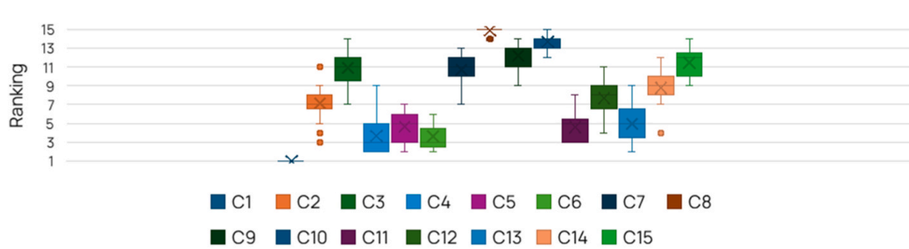

Fig. 4. Box plot visualizing the robustness of the components' influence ranking (by sum of the rows).

5.2. Answer to RQ2 – implications for alternative fuels adoption

The analysis of interdependencies provides insights into the cascade effects and necessary conditions for adopting sustainable fuels, such as hydrogen, in the maritime industry. Fig. 5 highlights the main clusters (in the figure named from A to F) of interdependencies to be managed for the adoption of sustainable fuels. These clusters are the result of interpreting results from the DEMATEL and insights from the literature: highly influential components (i.e., both core and driving components) appear first, relevant nodes are emphasised, and strong relationships are highlighted.

The first cluster is *A – Green fuel sourcing.* The DEMATEL remarks the importance of Subsystem 1 – *Fuel Value Chain*, specifically *C2 – Fuel Sourcing* and *C1 – Fuel Choice*, being core components. In particular, *C2 – Fuel Sourcing* emerges as the most influential process based on the significance indicator (*Ri-Ci* = 0.24), which reinforces the importance of ensuring a reliable, sustainable (i.e., "green") hydrogen supply (Shi et al., 2023). The relationship between these two processes is an antecedent to the other cascade effects. However, while these two processes are identified as core drivers in shaping the system, taking these decisions in the real world is complex. Generally, policy mandates and strategic directions from regulatory bodies (e.g., IMO or regional authorities) trigger the process, setting decarbonization targets and influencing transition pathways (IMO, 2023), (Ampah et al., 2021).

The second cluster is *B – Synergic fuel production.* Once the issue of sustainable energy sourcing is resolved, the production interests both *C3 – Fuel Production* and *C11 – Infrastructure Design. C3 – Fuel Production* is an independent factor with low prominence, driven mainly by other factors. However, it can gain prominence if couple with *C11 – Infrastructure Design.* The infrastructure of the port can serve a dual role, on one side to promote worldwide hydrogen trade (Chen et al., 2023) and on the other to be a hub, actively hosting the production of the fuel, as in the cases of the Port of Klaipeda and the Port of Amsterdam (Clean Hydrogen, 2023). Alternatively, it will be crucial to connect the production of the fuel to the infrastructure of the port through a strategically planned distribution network (Harahap et al., 2023).

The third cluster is *C – Catalytic infrastructure development*. The findings suggest a crucial interplay between Subsystem 3 – *Infrastructure Value Chain* and Subsystem 2 – *Shipbuilding Value Chain* (S3 → S2: 1.95). In particular, *C6 – Ship Design* is influenced by *C1 – Fuel Choice*, as well as *C11 – Infrastructure Design*, and *C13 – Infrastructure Operations*. At the same time, *C13 – Infrastructure Operations* is influenced by *C1 – Fuel Choice,* too. The implication is a potential bottleneck if shipbuilders advance the design and production of hydrogen-powered ships without corresponding port infrastructure readiness. As seen with more mature mobility transitions, such as the electrification of the automotive industry (Muratori et al., 2020), it appears that the infrastructure is the first that needs to be developed. Port authorities are encouraged to take a more active role in energy management to diversify energy sources and respond to environmental pressures, coordinating energy production and use, and adopting sustainable alternatives (Acciaro et al., 2014). However, port energy transition projects are complex and require collaborative efforts from stakeholders, who vary in importance, interests, and resources (Alamoush et al., 2024).

The results of the DEMATEL show that Subsystem 2 – *Shipbuilding Value Chain* has a limited outgoing influence on Subsystem *3 – Infrastructure Value Chain* (S2 → S3 is lower than the average relations between subsystems). The consequence is that early investments in port infrastructure can be effective in catalysing the system-wide transition, more than the immediate involvement of shipbuilders. The presence of ports equipped to handle hydrogen, or any of the other alternatives, can reduce uncertainty and de-risk the investment for shipowners and shipbuilders.

The fourth cluster is *D – Integrated ship design.* As mentioned earlier, *C1 – Fuel Choice* has important ramifications to the system, being a core factor, particularly at the crossroads that is represented by *C6 – Ship Design.* This cascade effect emphasizes the importance of designing ships for hydrogen from the start, rather than adjusting existing designs, to better integrate the required fuel systems and storage solutions (DNV, 2021). The high influence of *C14 – Sea Voyage*, another core factor, suggests that operational constraints, such as the range limitations associated with hydrogen storage density, will impact adoption pathways. This implies that a complete, immediate shift to hydrogen might not be feasible for all vessel types (e.g., long-haul cargo ships) without significant technological breakthroughs in storage or potentially the use of hydrogen carriers like ammonia or methanol (Harahap et al., 2023). As a consequence, ports will likely accommodate a mix of fuels for the foreseeable future (Aguilar et al., 2025).

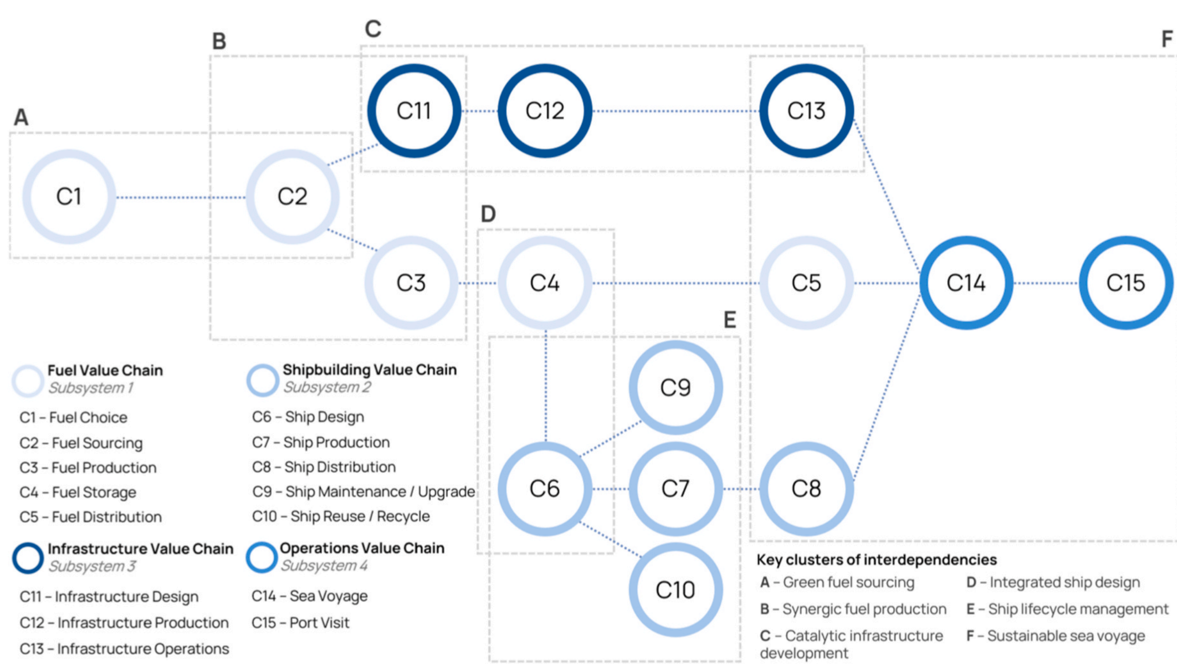

Fig. 5. Emergence in the maritime industry system-of-systems.

Table 6
Policy and managerial implications.

CAS term	Application to the maritime industry in the transition to sustainable fuels	Policy and managerial implications
System	Due to pressures for sustainability from the changing external environment, the maritime industry, as a complex, dynamic system-of-systems, must adapt to accommodate new fuels.	Policy makers and managers need to acknowledge the high degree of interdependence among decisions across the four maritime value chains. High $Ri + Ci$ values across components from all four subsystems confirm this.
Subsystems and Components	The subsystems are the four maritime value chains, and their processes are individual components: *1 – Fuel Value Chain* (C1-C5), *2 – Shipbuilding Value Chain* (C6-C10), *3 – Infrastructure Value Chain* (C11-C13), and *4 – Operations Value Chain* (C14-C15).	Individual efforts (e.g., a shipyard investing in a hydrogen design without clear signals on fuel availability or port readiness) represent a risk and can hardly produce positive results. The suggestion is to seek cross-value chain collaborations and establish common goals (e.g., Subsystem 1 – *Fue Value Chain* and Subsystem 3 – *Infrastructure Value Chain*). The institutions should play an auxiliary role in this process.
Autonomous Agents	The maritime industry consists of a range of actors (e.g., fuel producers, infrastructure managers, shipbuilders, shipowners) with conflicting objectives.	
Emergence	The six clusters (A–F) identified represent emergent behaviours from complex interactions, such as cluster *A – Green fuel sourcing* driving downstream effects across value chains.	In the initial stages of adoption, the policy efforts should concentrate on the core driving factors of the system (e.g., C1, C2, C6, C11, C13). In particular, the priority is to secure "green" fuel sources (C2) and manage the complexities of fuel choice (C1). These processes are concerning to upstream players, who deal with high uncertainty as a result of the emergence of numerous sustainable alternative fuels (Tagliapietra et al., 2019).
Co-evolution	Clusters *B – Synergic fuel production* and *C – Catalytic infrastructure development* co-evolve by means of *C2 – Fuel sourcing* and *C11 – Infrastructure Design.*	Infrastructure planning (C11) should be central to the transition, but flexible. Ports need the tools to develop, considering changing fuel technologies and availability. Policies should support multi-fuel infrastructure that can produce, store, and distribute fuel on site. Ports can become logistical hubs (Chen et al., 2023).
Learning and Adaptation	Port's *C13 – Infrastructure operations* adapt safety protocols and refuelling procedures based on hydrogen handling experience; shipbuilders revise *C6 – Ship Design* as new hydrogen technologies emerge.	The local port authorities and infrastructure developers soon come in as critical actors. The investments in storage and bunkering facilities at existing ports create the conditions to attract early adopters amongst shipowners (Acciaro et al., 2014). Policy should support these investments and coordinate the definition of standards.
Parallelism	*C7 – Ship production*, *C9 – Ship maintenance/upgrade*, and *C10 – Ship reuse/recycle* progress in parallel, advancing *E – Ship lifecycle management* and requiring coordination.	While ship upgrade (C9) and reuse (C10) appeared less influential within the system and were scarcely addressed in the literature, ignoring them would be shortsighted. The retrofits have enormous potential for facilitating the transition to a sustainable fuel system over the course of a ship's useful life (Soni et al., 2023). To support a "green" transition, policy can enhance these aspects by supporting research efforts and technology advancement in this direction.

The fifth cluster is *E – Ship lifecycle management*. The perceived low influence of *C9 – Ship Maintenance/Upgrade* and *C10 – Ship Reuse/Recycle* represents a strategic loss, potentially leading to future bottlenecks. Understandably, experts do not prioritize them at this time, considering the small number of hydrogen-fueled newbuilds sailing. To envision the recovery or retrofitting of them requires knowledge and skills yet to be formed at European shipyards (DNV, 2021). However, we believe their relevance should be anticipated to run in parallel with processes linked to newbuild ships, as *C6 – Ship Design* and *C7 – Ship Production*. These processes proved interdependent, and shipyards will need to decide where to allocate their resources. This is in line with existing practices and policies aimed at extending the lifecycle of ships and improving their end-of-life (e.g., EU's Ship Recycling Regulation). However, there will be a need to align existing practices to the specificities of hydrogen.

The sixth cluster is *F – Sustainable sea voyage*. Finally, we reach a point of convergence where ship, port, and fuel enable sustainable sea journeys by alternating between navigation and docking. Before doing so, the system must change at the same time, passing through a strategic planning of the cluster of interdependencies discussed thus far.

5.3. Policy and managerial implications

The DEMATEL results identify the behaviour and characteristics of the maritime industry's system-of-systems as it transitions to sustainable fuels. Table 6 summarizes the main characteristics of CAS, as defined in (Bale et al., 2015). The structuring into system, subsystems, and components typical of CAS proved helpful to grasp the many interdependencies at play. The study discusses a complex system, the maritime industry, but it does so by dividing it into four subsystems. These are the interdependent value chains: Subsystem 1 – *Fuel Value Chain*, Subsystem 2 – *Shipbuilding Value Chain*, Subsystem 3 – *Infrastructure Value Chain*, and Subsystem 4 – *Operations Value Chain*. Each comprises many processes to be carried out, which are understood as components of the subsystems. The autonomous agents are those responsible for each process. They are the diverse industry stakeholders who have been engaged in the DEMATEL study to produce an understanding of the CAS.

The DEMATEL analysis quantifies influence and causal roles to guide maritime industry recommendations. It is possible to study emergent behaviours of the system as a result of complex interactions, such as those caused by changing the dominant fuel option. Co-evolution, learning and adaptation, and parallelism are other mechanisms that are common among CAS components. The quantitative findings and qualitative readings in light of current research have directly influenced policy directions based on the fundamental properties of the CAS under consideration, its emergent behaviours, and the interactions of its components. Specifically, components with high significance ($Ri + Ci >$ 6.0) and positive relation ($Ri\text{-}Ci > 0$), such as C1, C11, and C13, are identified as strategic leverage points for actions to have the biggest systemic impact. Conversely, components with a negative relation ($Ri\text{-}Ci < 0$), such as C5 and C15, identify dependencies that need further support. Overall, the results' interpretation sheds light on the implications of hydrogen adoption for managers in all four value chains, as well as policy makers. Table 6 summarizes these policy and managerial implications.

First, policy makers and managers must recognize the high interdependence across the four value chains, as high $Ri + Ci$ values demonstrate. Consequently, isolated actions, such as a shipyards pushing hydrogen-powered newbuilds without confirmed fuel supply or port readiness to follow, are risky (Tagliapietra et al., 2019). Upcoming policies should promote cross-chain connections. For instance, governments can spur the creation of multi-stakeholder working groups including fuel producers (Subsystem 1 – *Fuel Value Chain*), shipyards (Subsystem 2 – *Shipbuilding Value Chain*), port authorities (Subsystem 3 – *Infrastructure Value Chain*), and service providers (Subsystem 4 – *Operations Value Chain*) to align timelines, technical standards, and safety measures.

Second, in the early adoption phase, policy should focus on core system drivers (C1, C2, C6, C11, C13) to generate significant impact. Specifically, *C2 – Fuel Sourcing* can be supported via off-take agreements, public-private partnerships, or tax incentives for early investment in ammonia, hydrogen, or methanol production plants (IEA, 2023). To manage *C1 – Fuel Choice* complexity, policy makers and industry stakeholders can work to formulate fuel standards (e.g., ISO 14687:2025 Hydrogen fuel quality – Product specification), reducing uncertainty for shipowners and upstream producers (IEA, 2023), (ISO, 2025), (EMSA, 2023). *C11 – Infrastructure Design* must be flexible, multi-fuel, and future-proof. Examples, in Europe, include Rotterdam and Antwerp multi-fuel bunkering terminals (Sornn-Friese, 2024).

Third, local port authorities and infrastructure developers can be rewarded with grants, co-financing, or low-interest loans for upgrading existing infrastructure, attracting early adopters among shipowners (Acciaro et al., 2014). Even if retrofitting and reuse (C9, C10) have a smaller impact in the short term, the lifecycle of hydrogen-powered ships should be considered (Soni et al., 2023). Policy mechanisms that are moving in this direction include R&D funding and retrofit tax credits. Some examples include Norway's retrofit subsidies and Denmark's "Green Ship of the Future" program, which can speed up fleet conversion to green fuels (GSF), (Tvedten and Bauer, 2022). Digital decision-support tools (e.g., based on digital twins) can improve retrofit planning, fuel deployment, and route logistics while ensuring the coherence of the system (Liu et al., 2024).

6. Conclusions

This study investigates the transition of the maritime industry to hydrogen from a system's perspective, to draw suggestions for policy making. The maritime industry is seen as a CAS, in which four interconnected subsystems, i.e., four value chains, made of components, i.e., processes, interact. Leveraging the DEMATEL method, the study shows the complex web of cause-and-effect relationships across the value chains (i.e., fuel, shipbuilding, infrastructure, and operations). The results demonstrate how decisions or constraints in one area (e.g., fuel energy sourcing) have an impact on the feasibility and pace of other areas (e.g., ship design, port operations). The results identify certain processes as "causes" (e.g., *C1 – Fuel Choice*, *C2 – Fuel Sourcing*) as opposed to "effects" (e.g., *C9 – Ship Maintenance/Upgrade*, *C10 – Ship Reuse/Recycle*, *C15 – Port Visit*). The study outlines the most relevant dynamics of the complex system, providing the basis to inform transition pathways.

From a theoretical standpoint, this paper contributes to our understanding of energy transitions by using CAS theory to analyse the transition to sustainable fuels. The research contributes to the literature on maritime decarbonization by quantifying the value chain interdependencies, which were previously studied qualitatively and fragmentarily. We approached the challenge of sustainable fuel adoption from a value chain perspective by providing a point of view that complements existing studies on technological feasibility.

While this study focuses on the maritime system's structural interdependencies, the cause-and-effect relationships provide a strong basis that can be directly integrated with other relevant approaches (e.

g., quantitative environmental performance assessments). The cause-and-effect relationships can help in the definition of the key decision pathways that govern the maritime industry's system-of-systems. Starting from this structure, future research can integrate Life Cycle Assessment (LCA) or Well-to-Wake (WtW) models. For instance, the core factors (e.g., C1, C2, C6, C11) represent turning points where decision (e.g., the adoption of certain technological solutions or sourcing strategies) generate considerable cascade effects, ultimately defining different environmental scenarios. Combining the two would allow policy makers to evaluate not only how decisions cascade, as shown in this study, but also the resulting GHG emissions, or other impacts, for systemic optimization.

When it comes to managerial and policy implications, the findings offer several practical cues for decision-makers across the maritime industry. We emphasise the relevance of taking a coordinated, system-wide approach when defining policies and actions. The policies and investments must prioritize securing a sustainable fuel supply and enable port infrastructure to develop as a catalyst for the transition. Then, the planning for the full lifecycle of new ships is also critical for long-term success. This research provides a structured outline of interdependencies of the maritime complex system-of-systems and actionable insights for policy makers and industry stakeholders to pursue maritime decarbonization.

The research has some limitations. First, the research is contextualized in the European maritime industry, drawing on insights from participants from 7 European countries. The results may not fully capture regional disparities in port infrastructure, policy maturity, and technological readiness at a global level. Second, while the sample size is consistent with DEMATEL methodology, having more participants would improve the reliability of the causal structure. Future research should aim to replicate this analysis in other geographical contexts, comparing pathways to the hydrogen transition across countries.

With respect to generalization, we shall distinguish two layers in the analysis. On one side, key differences exist at the microscopic level when it comes to different sustainable fuels, including storage, safety restrictions, and infrastructure requirements. However, at the macroscopic level, all value chains must commit to aligning shipbuilding, fuel production, operations, and infrastructure to transition to the use of sustainable fuels. Overall, the more appropriate way forward is to investigate the specifics of each fuel for targeted policies.

Future research shall perform empirical testing or simulation validation of the study's results. In particular, it can be accomplished by addressing segments of value chains at a time, or even specific relationships. Ultimately, the contribution of this research stands in the comprehensive nature of a DEMATEL, which satisfies the need to produce high-level policy recommendations from a system's perspective.

CRediT authorship contribution statement

Francesca Bianchi: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Margherita Pero:** Writing – review & editing, Methodology, Conceptualization. **Monica Rossi:** Writing – review & editing, Investigation, Conceptualization.

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article or its supplementary materials.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We acknowledge financial support under the National Recovery and Resilience Plan (NRRP), funded by the European Union.

Appendix

Appendix A
Standard deviation of the total-relation matrix (X)

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	Avg
C1		0.92	1.30	0.28	0.62	1.04	0.91	1.11	0.50	0.95	0.65	0.76	0.95	1.41	1.18	0.90
C2	0.76		1.40	1.16	1.25	1.23	1.38	1.01	1.11	1.01	1.19	1.04	1.19	1.37	1.25	1.17
C3	1.41	1.47		1.69	1.50	0.95	0.76	0.64	1.01	0.94	1.31	1.26	1.46	0.85	0.99	1.16
C4	0.43	1.36	1.63		1.16	1.22	1.37	1.15	0.99	1.04	1.38	1.28	1.44	1.63	1.63	1.27
C5	0.62	1.32	1.21	0.92		1.30	1.07	0.87	1.28	0.99	0.76	1.09	1.29	1.64	1.55	1.14
C6	1.34	1.40	1.15	1.28	1.30		0.86	1.37	0.95	0.96	0.92	1.04	1.15	1.53	1.38	1.19
C7	1.32	1.38	0.90	1.55	1.21	1.19		1.52	1.48	1.30	1.30	1.15	1.28	1.66	1.42	1.33
C8	1.08	0.76	0.76	0.85	0.76	1.55	1.31		1.48	1.42	1.29	1.14	0.99	1.01	0.72	1.08
C9	1.19	0.99	0.85	0.95	0.85	1.15	1.38	1.44		1.40	0.94	0.86	1.19	1.07	1.04	1.09
C10	1.11	1.19	0.86	0.92	1.11	1.04	1.42	1.49	1.36		0.99	1.21	0.76	1.26	0.80	1.11
C11	0.49	1.14	1.40	1.15	0.65	1.26	1.23	0.85	1.14	1.04		1.44	1.48	1.55	1.28	1.15
C12	0.86	1.32	1.38	1.19	1.37	1.16	1.14	1.01	1.11	1.03	1.11		1.21	1.43	1.58	1.21
C13	0.76	1.36	1.26	1.19	0.76	1.53	1.22	1.11	1.26	0.80	1.18	1.14		1.47	1.48	1.18
C14	1.36	1.61	1.08	1.30	1.38	1.41	1.43	1.38	1.04	1.00	1.26	1.18	1.29		1.32	1.29
C15	1.23	1.23	1.07	1.26	1.34	1.37	1.26	1.00	1.09	1.07	1.11	1.34	1.30	1.32		1.21

Avg: average.

Appendix B

Sensitivity analysis using as input data the total-relation matrix (X) with values randomized around their standard deviation and ranking of components by influence (sum of the rows).

	RUN 0		RUN 1		RUN 2		RUN 3		RUN 4		RUN 5		RUN 6		RUN 7		RUN 8		RUN 9		RUN 10	
	Row sum	Rank	Row sum	Rank	Rowsum	Rank	Rowsum	Rank	Rowsum	Rank	Rowsum	Rank	Rowsum	Rank	Rowsum	Rank	Rowsum	Rank	Rowsum	Rank	Rowsum	Rank
C1	3.64	1	3.54	1	3.27	1	3.22	1	3.1	1	3.91	1	3.66	1	3.69	1	3.53	1	3.34	1	4.48	1
C2	2.76	7	2.89	6	2.42	7	2.07	9	2.22	7	2.98	7	2.68	8	2.97	7	2.54	8	2.69	5	3.86	6
C3	2.27	10	2.29	10	1.5	13	2.03	12	1.97	9	2.21	14	2.5	10	2.5	9	1.76	14	2.26	10	3	11
C4	3.09	2	2.73	9	2.56	5	2.76	2	2.63	2	3.51	2	3.46	2	3.12	4	2.93	4	2.73	3	4.42	2
C5	3.05	5	2.85	7	3.08	2	2.31	6	2.26	5	3.25	6	3.18	4	3.3	2	2.78	6	2.57	6	3.88	5
C6	3.07	3	3.16	2	2.68	3	2.59	3	2.54	3	3.31	4	2.78	6	2.97	6	2.84	5	2.74	2	3.9	3
C7	2.24	12	1.79	12	1.93	11	2.14	8	1.76	10	2.59	11	2.32	12	2.38	11	2.34	11	2.04	11	3.36	8
C8	1.47	15	1.42	15	1.23	15	1.3	15	0.83	15	1.45	15	1.13	15	1.38	15	1.37	15	1.28	15	1.86	15
C9	2.07	13	1.97	11	1.89	12	1.86	13	1.5	14	2.34	12	1.65	13	2.4	10	2.41	9	1.67	13	2.48	13
C10	1.79	14	1.76	13	1.45	14	1.58	14	1.64	12	2.23	13	1.45	14	1.65	14	1.85	13	1.44	14	2.66	12
C11	3.07	4	3.13	3	2.59	4	2.49	5	2.25	6	3.44	3	3.37	3	3.18	3	2.96	3	2.44	8	3.77	7
C12	2.6	8	3.04	5	2.26	9	2.06	10	2.18	8	2.86	8	2.39	11	3.03	5	2.54	7	2.29	9	3.31	9
C13	3	6	3.1	4	2.48	6	2.27	7	2.44	4	3.31	5	2.93	5	2.86	8	3.12	2	2.71	4	3.9	4
C14	2.52	9	2.74	8	2.29	8	2.57	4	1.65	11	2.81	9	2.75	7	2.34	12	2.39	10	2.56	7	3.25	10
C15	2.27	11	1.61	14	2.11	10	2.03	11	1.62	13	2.67	10	2.68	9	2.31	13	2.07	12	2.03	12	2.27	14

RUN 11		RUN 12		RUN 13		RUN 14		RUN 15		RUN 16		RUN 17		RUN 18		RUN 19		RUN 20		
Row sum	Rank	Row sum	Rank	Row sum	Rank	Row sum	Rank	Row sum	Rank	Row sum	Rank	Row sum	Rank	Row sum	Rank	Row sum	Rank	Row sum	Rank	SD
4.17	1	3.13	1	3.50	1	3.60	1	3.55	1	4.44	1	4.20	1	2.92	1	3.47	1	3.81	1	0
3.20	7	2.21	7	2.90	3	2.60	9	2.99	4	3.06	11	3.36	8	1.90	8	2.56	8	2.70	8	1.70
2.87	9	2.03	9	2.05	11	2.03	12	2.52	10	3.02	12	2.49	12	1.30	13	1.95	12	2.88	7	1.80
3.64	5	2.57	3	2.76	6	3.04	4	2.97	5	4.00	3	3.87	3	2.22	6	2.87	3	3.56	2	1.78
3.80	4	2.53	4	2.79	5	2.94	6	2.76	6	4.41	2	3.37	7	2.51	2	3.04	2	3.21	6	1.70
3.90	2	2.25	6	2.86	4	3.27	2	3.04	2	3.94	4	3.81	4	2.45	3	2.74	6	3.49	3	1.40
2.75	10	1.96	11	1.67	13	2.35	10	2.23	11	3.50	7	2.40	13	1.55	10	2.14	11	2.27	12	1.52
1.65	15	0.85	15	1.36	15	1.55	15	1.29	15	1.96	15	1.99	14	1.27	14	1.12	15	1.48	15	0.29
2.29	13	1.59	13	2.03	12	1.71	14	1.72	13	2.47	13	2.51	11	1.49	11	2.33	10	2.19	13	1.33
2.26	14	1.29	14	1.41	14	1.92	13	1.69	14	1.98	14	1.92	15	0.96	15	1.56	14	1.93	14	0.76
3.82	3	2.47	5	2.64	7	2.96	5	3.02	3	3.77	5	3.64	6	2.25	5	2.78	5	3.34	4	1.50
3.09	8	1.99	10	2.43	9	2.68	7	2.75	7	3.77	6	3.71	5	1.99	7	2.80	4	2.66	9	1.83
3.63	6	2.76	2	3.09	2	3.07	3	2.66	8	3.50	8	4.07	2	2.34	4	2.52	9	3.28	5	2.13
2.65	11	2.03	8	2.43	8	2.64	8	2.54	9	3.37	9	2.98	10	1.84	9	2.62	7	2.42	10	1.72
2.44	12	1.76	12	2.39	10	2.15	11	2.09	12	3.37	10	3.30	9	1.48	12	1.60	13	2.36	11	1.43

SD: standard deviation across the twenty iterations.

Appendix C

The twelve expert assessment matrices used to calculate the direct-relation matrix (X)

ID: 1

Expert: Port and Infrastructure

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
C1		3	4	4	2	4	1	1	2	2	3	3	3	3	3
C2	3		4	3	3	1	1	1	0	0	3	3	3	2	2
C3	4	4		4	4	3	2	1	2	2	3	3	3	2	2
C4	4	3	4		4	4	3	2	3	2	2	1	2	3	3
C5	2	3	4	4		1	1	1	2	2	3	1	2	3	3
C6	4	1	3	4	1		3	3	4	4	2	2	2	4	4
C7	1	1	2	3	1	3		2	3	3	2	1	1	0	0
C8	1	1	1	2	1	3	2		1	2	1	1	1	2	1
C9	2	0	2	3	2	4	3	1		4	2	1	1	2	2
C10	2	0	2	2	2	4	3	2	4		1	0	0	1	1
C11	3	3	3	2	3	2	2	1	2	1		4	4	3	2
C12	3	3	3	1	1	2	1	1	1	0	4		4	3	4
C13	3	3	3	2	2	2	1	1	1	0	4	4		3	3
C14	3	2	2	3	3	4	0	2	2	1	3	3	3		4
C15	3	2	2	3	3	4	0	1	2	1	2	4	3	4	

ID: 2

Expert: Port and Infrastructure

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
C1		4	4	4	4	4	3	3	3	2	4	4	4	1	1
C2	4		3	3	3	2	2	2	2	1	1	1	1	1	1
C3	4	4		4	4	1	1	1	1	0	3	3	3	0	0
C4	4	4	4		4	4	4	3	3	2	0	0	0	0	0
C5	4	4	4	4		0	0	0	0	3	3	3	0	0	0
C6	4	4	3	4	2		4	4	4	4	2	2	2	0	0
C7	4	4	3	4	4	4		4	4	4	3	3	3	0	0
C8	0	0	0	0	0	4	4		4	4	3	3	3	2	0
C9	0	0	0	0	0	4	4	4		4	2	2	2	4	1
C10	0	0	0	0	0	4	4	4	4		0	0	0	4	1
C11	4	4	4	4	4	1	1	1	1	1		4	4	1	4
C12	4	4	4	4	4	1	1	1	1	1	4		4	1	4
C13	4	4	4	4	4	1	1	1	1	1	4	4		1	4
C14	4	4	2	4	4	1	1	1	1	1	1	1	1		1
C15	1	1	1	1	1	1	1	1	1	1	1	1	1	1	

ID: 3

Expert: Fuel

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
C1		3	4	4	4	1	1	0	3	3	4	3	4	0	3
C2	2		3	2	1	0	0	0	1	0	3	3	3	0	0
C3	3	3		1	0	0	0	0	0	0	3	3	3	0	1
C4	3	1	1		4	2	0	0	3	1	4	4	4	0	3
C5	3	1	1	3		2	1	0	1	1	3	1	4	0	3
C6	0	0	0	1	1		2	1	3	3	1	0	1	4	3
C7	0	0	0	0	0	2		0	1	1	0	0	0	0	0
C8	0	0	0	0	0	0	0		0	2	1	0	1	2	1
C9	2	0	0	1	2	2	1	1		3	2	0	2	3	3
C10	2	0	0	2	1	2	1	1	3		0	0	0	1	2
C11	3	3	2	3	4	2	1	0	1	1		3	4	1	3
C12	2	1	1	3	1	0	1	0	0	0	3		2	0	1
C13	3	3	3	4	4	1	0	1	2	2	3	3		1	4
C14	0	0	0	0	1	2	1	2	2	2	1	0	2		3
C15	0	0	0	1	1	1	1	2	2	1	2	1	3	3	

ID: 4

Expert: Shipbuilding

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
C1		1	1	4	4	3	2	2	3	4	3	3	4	2	4
C2	4		2	3	4	2	2	3	3	2	3	3	2	2	4
C3	3	2		1	2	1	1	2	3	2	4	4	4	2	3
C4	4	3	3		3	4	3	3	3	3	3	2	3	3	4
C5	4	3	3	2		4	2	3	3	2	4	3	3	4	4
C6	3	2	2	3	2		2	2	3	4	2	2	2	2	2
C7	2	3	1	1	1	2		2	3	3	2	2	2	2	2
C8	2	2	1	1	1	2	2		2	2	2	2	2	1	1
C9	3	2	2	2	2	3	3	2		4	2	2	2	3	3
C10	3	3	2	2	1	4	2	3	3		2	2	2	3	2
C11	3	3	3	3	3	3	2	1	2	1		3	3	4	4

(continued on next page)

Appendix C (*continued*)

ID: 4

Expert: Shipbuilding

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
C12	3	3	3	2	4	2	2	2	2	2	3		3	3	3
C13	2	3	2	2	3	3	1	1	1	1	3	3		3	3
C14	4	4	1	3	2	4	2	2	3	3	3	2	3		3
C15	4	4	2	2	3	3	2	2	4	4	3	2	3	2	

ID: 5

Expert: Fuel

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
C1		3	4	4	4	3	2	1	2	2	4	4	3	2	2
C2	3		3	4	3	2	4	2	3	3	3	3	3	2	2
C3	4	4		4	2	1	0	0	0	0	1	1	0	1	1
C4	4	3	0	0	4	3	3	1	3	2	2	2	3	4	4
C5	4	2	3	3		3	3	1	4	2	2	2	3	3	4
C6	1	1	0	2	0		4	3	4	4	2	2	2	4	3
C7	1	2	1	3	2	4		4	4	3	2	2	2	4	3
C8	2	0	0	0	0	3	3		2	2	0	0	0	3	1
C9	1	1	2	2	0	3	3	1		3	1	2	2	2	1
C10	0	2	0	2	0	2	1	1	3		1	1	1	1	0
C11	4	3	4	4	4	2	3	1	0	0		4	4	1	4
C12	3	2	2	2	2	2	0	0	0	0	4		4	0	3
C13	2	3	2	4	4	2	3	2	2	2	2	3		0	4
C14	3	3	3	2	4	5	3	4	2	2	2	1	1		2
C15	1	1	0	3	2	1	1	0	0	0	4	4	3	3	

ID: 6

Expert: Fuel

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
C1		2	4	4	3	4	3	3	2	2	3	2	2	2	3
C2	2		4	1	1	1	1	1	2	2	1	1	1	1	1
C3	4	4		2	3	2	1	1	1	2	3	2	2	1	1
C4	4	2	2		2	4	2	2	2	2	3	3	3	4	4
C5	4	1	1	3		1	1	1	1	1	4	4	3	4	4
C6	4	1	1	2	2		4	4	4	4	3	3	2	1	1
C7	3	1	1	1	1	3		4	4	4	4	3	4	3	3
C8	3	1	2	2	2	4	4		4	4	4	3	2	2	2
C9	2	2	1	1	1	4	4	4		4	3	2	3	2	2
C10	2	2	2	2	3	4	4	4	3		2	2	2	1	1
C11	3	1	3	3	3	3	4	3	4	3		4	4	4	4
C12	2	1	3	3	3	3	4	3	3	2	3		4	4	4
C13	2	1	3	3	3	4	4	4	4	2	4	4		4	4
C14	2	3	2	2	3	4	4	4	4	2	3	3	3		4
C15	3	1	2	3	4	3	3	3	1	1	3	3	3	4	

ID: 7

Expert: Shipbuilding

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
C1		4	4	4	4	4	2	2	3	2	4	4	4	4	4
C2	4		4	1	1	0	0	0	0	0	1	4	4	0	0
C3	4	4		4	4	0	0	0	0	0	4	4	4	0	0
C4	4	1	4		4	0	0	0	0	0	4	4	4	0	0
C5	4	1	4	4		0	0	0	0	0	4	4	4	0	0
C6	4	0	0	0	0		4	4	4	4	4	3	4	4	4
C7	2	0	0	0	0	4		3	3	3	1	0	0	1	0
C8	2	0	0	0	0	4	3		0	0	0	0	0	0	0
C9	3	0	0	0	0	4	3	0		3	2	0	4	3	1
C10	2	0	0	0	0	4	3	0	3		3	0	1	0	1
C11	4	1	4	4	4	4	1	0	2	3		4	4	0	3
C12	4	4	4	4	4	3	0	0	0	0	4		4	3	3
C13	4	4	4	4	4	4	0	0	4	1	4	4		3	3
C14	4	0	0	0	0	4	1	0	3	0	0	3	3		1
C15	4	0	0	0	0	4	0	0	1	1	3	3	3	1	

ID: 8

Expert: Maritime operations and services

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
C1		4	4	4	4	2	1	0	2	1	4	3	3	3	3
C2	4		4	4	4	2	1	0	1	1	4	2	3	3	3
C3	4	4		4	4	1	0	0	0	0	4	2	3	2	2
C4	3	3	3		4	3	1	0	2	0	4	2	4	3	3

(*continued on next page*)

Appendix C (*continued*)

ID: 8

Expert: Maritime operations and services

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
C5	4	3	4	4		2	0	0	0	1	4	2	4	3	3
C6	2	2	2	3	3		4	2	4	4	2	1	3	3	3
C7	1	1	1	2	1	3		1	3	3	1	1	1	1	1
C8	2	2	2	2	2	2	2		3	3	1	1	1	1	1
C9	1	1	1	1	1	3	3	3		3	1	1	1	1	1
C10	1	1	1	1	1	2	2	3	4		1	1	1	2	2
C11	3	3	3	4	3	2	1	1	1	1		3	4	3	3
C12	2	2	2	3	3	2	1	2	3	3	3		3	1	1
C13	3	3	3	3	3	3	1	1	1	1	4	2		3	3
C14	3	3	2	3	3	3	1	1	1	1	3	2	3		3
C15	3	3	3	3	3	3	1	1	1	1	3	1	3	3	

ID: 9

Expert: Fuel

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
C1		4	4	4	4	4	1	1	3	2	4	3	4	3	4
C2	4		4	4	4	4	0	0	2	2	4	2	4	1	1
C3	0	4		0	0	0	0	0	0	0	0	0	0	0	0
C4	4	0	0		0	4	4	0	3	3	4	3	4	2	2
C5	4	0	2	4		3	3	0	0	0	4	3	4	3	4
C6	4	1	1	4	4		4	4	4	4	4	2	4	4	4
C7	4	1	1	1	1	4		1	4	4	0	0	0	0	0
C8	0	0	0	0	0	2	2		3	0	0	0	0	0	0
C9	4	0	0	2	0	3	3	0		2	0	0	0	3	3
C10	2	0	0	0	0	3	3	0	2		0	0	0	0	0
C11	4	2	4	4	4	4	0	0	0	0		0	0	4	4
C12	4	0	3	4	0	0	0	0	0	0	4		2	0	0
C13	4	0	3	4	4	4	1	0	0	0	4	4		0	4
C14	3	0	0	2	0	4	3	0	2	0	0	0	0		0
C15	1	0	0	4	4	4	0	0	0	0	4	2	4	0	

ID: 10

Expert: n.d.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
C1		4	0	4	4	4	4	0	2	0	3	2	2	0	2
C2	4		0	1	1	1	4	0	0	0	4	4	4	4	2
C3	0	0		0	1	0	0	0	0	0	1	1	0	0	0
C4	4	0	0		3	2	2	0	1	0	0	0	0	1	0
C5	4	4	1	1		3	1	0	1	0	4	4	4	3	3
C6	4	4	0	4	3		4	1	1	1	1	0	1	4	2
C7	4	4	0	4	3	4		1	0	1	0	0	1	4	2
C8	0	0	0	0	0	0	2		0	0	0	0	0	0	0
C9	2	1	0	0	0	2	0	0		0	0	0	0	1	0
C10	0	0	0	0	0	1	0	0	0		0	4	0	0	0
C11	3	0	0	0	4	0	0	0	0	0		4	4	0	1
C12	2	0	0	0	4	0	0	0	0	0	4		4	0	0
C13	2	0	0	0	4	0	0	0	1	0	4	3		2	1
C14	0	2	0	1	3	2	0	0	1	0	0	0	1		2
C15	2	2	0	2	3	1	0	0	1	0	2	0	1	2	

ID: 11

Expert: Port and Infrastructure

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
C1		4	3	4	4	2	2	0	3	3	4	4	3	4	3
C2	4		0	4	4	4	0	0	3	2	1	1	1	4	0
C3	3	0		0	4	0	0	0	0	0	4	4	3	0	0
C4	4	4	0		4	4	4	1	1	2	3	3	3	4	1
C5	4	4	4	4		0	0	0	0	0	4	4	4	4	2
C6	2	4	0	4	0		4	4	4	4	2	0	0	3	3
C7	2	0	0	4	0	4		4	4	4	0	0	0	4	4
C8	0	0	0	1	0	4	4		2	2	0	0	0	2	2
C9	3	3	0	1	0	4	4	2		4	1	1	1	2	2
C10	3	2	0	2	0	4	4	2	4		0	0	0	0	0
C11	4	1	4	3	4	2	0	0	1	0		4	4	2	2
C12	4	1	4	3	4	0	0	0	1	0	4		4	1	1
C13	3	1	3	3	4	0	0	0	1	0	4	4		4	0
C14	4	4	0	4	4	3	4	2	2	0	2	1	4		2
C15	3	0	0	1	2	3	4	2	2	0	2	1	0	2	

ID: 12

(*continued on next page*)

Appendix C (*continued*)

ID: 12

Expert: Shipbuilding

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
Expert: Shipbuilding															
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
C1		3	3	3	3	2	2	0	2	2	2	2	1	0	0
C2	3		3	3	3	2	2	0	2	2	2	2	1	0	0
C3	3	3		3	3	2	2	0	2	2	2	2	1	0	0
C4	3	3	3		3	2	2	0	2	2	2	2	1	0	0
C5	3	3	3	3		2	2	0	2	2	2	2	1	0	0
C6	2	2	0	3	3		2	0	2	2	2	2	1	0	0
C7	1	1	0	0	0	0		0	0	0	0	0	0	0	0
C8	0	0	0	0	0	0	0		0	0	0	0	0	0	0
C9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C10	3	3	0	2	3	3	0	0	0		0	0	0	0	0
C11	3	2	0	2	2	0	0	0	0	0		0	0	0	0
C12	2	2	0	2	2	0	0	0	0	0	0	0	0	0	0
C13	3	2	0	2	2	0	0	0	0	0	0	0		0	0
C14	3	0	0	3	3	0	0	0	0	0	0	0	0		0
C15	2	1	0	0	0	0	0	0	0	0	0	0	0	0	

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