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A roadmap to alternative fuels for decarbonising shipping: The case of green ammonia

Gökcay Balci [a], Thi Tuyet Nhung Phan [b], Ebru Surucu-Balci [a], Çağatay Iris [c,*]

[a] *School of Management, University of Bradford, Bradford, United Kingdom*
[b] *BigChange Limited, Leeds, United Kingdom*
[c] *University of Liverpool Management School, Liverpool, United Kingdom*

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ABSTRACT

Decarbonisation efforts in shipping have intensified amid recent regulations and net-zero emission pledges from governments and global supply chains. Green ammonia is one of the alternative fuels that can accomplish net-zero targets of the industry. However, considerable challenges exist for green ammonia adoption as the future clean energy source in maritime transport. This study scrutinises the success factors of the industry-wide adoption of green ammonia. We examine the structural relationship between success factors to explore antecedents, illustrate the precedence relationships between success factors, and present a roadmap. We first determine success factors and then employ Interpretive Structural Modelling (ISM) and Cross-Impact Matrix Multiplication Applied to Classification (MICMAC) to reveal relationship between success factors and suggest a roadmap. The success factors of an alternative fuel adoption are the availability of the fuel, the cost of the fuel, R&D in the fuel, safety regulations of the fuel, propulsion technology, port infrastructure for the fuel, stakeholder support, setting of carbon tax, public awareness on emissions and early adopter companies using the fuel. 48 experts completed the ISM survey for green ammonia. Results indicate that the most fundamental success factors are stakeholder support, carbon taxation, public awareness, and the number of early adopters. These fundamental success factors would pave the way to safety regulations of ammonia and R&D progress, which would then improve ammonia-powered propulsion systems and support a vast availability of green ammonia. Following the accomplishment of the above listed success factors, ammonia cost reduction and port infrastructure development can be delivered.

1. Introduction

There are more than 100,000 ships of 100 gross tons and above sailing around the world in 2023 (UNCTAD, 2023). Particularly, maritime transport is the primary mode of cargo transport in most supply chains, carrying more than %80 of the volume of the global trade. Maritime transport of passengers also constitutes an important economic segment with around 4000 ships. In 2018, the GHG emissions of overall shipping industry has been reported as 1076 million tonnes, accounting approximately for 2.8% of all GHG emissions (IMO, 2020). Maritime transport is still acknowledged as a greener option compared to air, road, and rail transport considering GHG emissions per tonne-km (UNCTAD, 2023). Given the facts that the shipping industry has a large and rapidly growing fleet size, uses dirtiest fuels commonly available (e.g. HFO) and impacts coastal and marine life directly, sustainable shipping targets and initiatives are paramount to reduce the negative environmental impact of the industry.

The UNFCCC Paris Agreement goals for action on climate change are set at COP21 in 2015 and cover all GHG emissions – including shipping. The Paris Agreement and 2030 Agenda for Sustainable Development

Abbreviations: COP, Conference of the Parties; MICMAC, Cross-Impact Matrix Multiplication Applied to Classification; GHG, Greenhouse Gas; CSF, Critical Success Factor; DNP, Dependency Powers; DRP, Driving Power; ETS, Emissions Trading Scheme; EEDI, Energy Efficiency Design Index; FRM, Final Reachability Matrix; HFO, Heavy Fuel Oil; ISM, Interpretive Structural Modelling; IRM, Initial Reachability Matrix; IMO, International Maritime Organisation; ISM, Interpretive structural modelling; LH2, Liquified Hydrogen; LNG, Liquified Natural Gas; MDO, Marine Diesel Oil; MGO, Marine Gas Oil; NOx, Nitrogen oxides; NGO, Non-government Organisations; PM, Particulate Matter; R&D, Research and Development; SSIM, Structural Self-Interaction Matrix; SOx, Sulphur oxides; UNFCCC, United Nations Framework Convention on Climate Change.

* Corresponding author at: Chatham St., Liverpool L69 7ZH, United Kingdom.
E-mail address: c.iris@liverpool.ac.uk (Ç. Iris).

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pave the way for a sustainable, low-carbon and resilient development under a changing climate. In this scope, the maritime regulatory body, the IMO, published a revised GHG reduction strategy in 2023 which identifies four goals: 1) to reduce CO2 emissions by minimum 40% by 2030, compared to 2008 levels, 2) the uptake of zero or near-zero GHG emission technologies, fuels and/or energy sources to represent at least 5% of the energy used by shipping by 2030, 3) to reduce carbon intensity of the ship through the energy efficiency improvements for new incoming ships, and 4) to reach net-zero GHG emissions close to 2050 (IMO, 2023; Zheng, Li, & Song, 2022). The in-place IMO regulations on the sulphur cap of marine bunker fuels and the emission control areas are also part of the sustainable shipping initiative. Countries publish plans to achieve listed IMO goals. For example, the UK intends to roll out net-zero emission shipping routes in collaboration with the US, Norway and the Netherlands as a part of COP27 pledge in 2022 and recommends new-built ships to have zero-emission propulsion capability by 2025 (MaritimeUK, 2022).

However, the path to decarbonise the shipping industry is not straightforward and is open to debate (Leeuwen & Monios, 2022; McKinlay, Turnock, & Hudson, 2021). Conventional bunker fuels including HFO, MDO, and MGO have dominated the shipping fuel market for many decades, and alternative fuels have been mostly overlooked until recent years. Alternative fuels usage has been very limited on commercial scale, yet a transition towards wider adoption of alternative sources of energy is now a primary objective of the shipping industry (Thomas, 2021). Although numerous cleaner technology options are assessed in maritime transport such as wind power, solar energy and battery-based propulsion (DNV GL, 2019), alternative fuels are a common candidate as a medium-to-long term solution for both short-sea and deep-sea shipping.

Ammonia as a carbon-free molecule is one of the promising alternative fuels. Specifically, green ammonia, whose production is completely from renewable and carbon-free resources, is the subject of this study. Several critical factors impact alternative fuels uptake, yet the state-of-the-art has mostly focused on costs and engineering details. The successful adoption of green ammonia depends on several factors which are not well studied in the state-of-the-art. Success factors are multidimensional involving technical, economic, regulatory, social and supply chain elements (Mäkitie, Steen, Saether, Bjørgum, & Poulsen, 2022). For instance, the price of green ammonia should be reduced to attract more adoption as a fuel. Ammonia-fuelled propulsion systems or ammonia-based fuel cells should be designed and improved to enable vessels to run with green ammonia (Inal, Zincir, & Deniz, 2022). Moreover, an international regulatory framework should be designed for ammonia as a fuel to determine safety and security standards. The process of adoption is too complicated for a single organisation to tackle all challenges; thus, stakeholder collaboration and public awareness play key roles as well (DNV GL, 2019).

The complex nature of green ammonia adoption compels the examination of relationships between success factors. The literature points out some barriers and antecedents of alternative fuels, yet the structural relationships between them are unknown. For instance, the cost of green ammonia may impact the increase in R&D and the availability of green ammonia (Ash & Scarbrough, 2019). Conversely, R&D and supply maximisation can also lead to a reduction in cost (Al-Aboosi, El-Halwagi, Moore, & Nielsen, 2021). Stakeholder collaboration may facilitate the introduction of a regulatory framework, or stakeholders might be willing to collaborate more if the regulatory framework is designed first. Moreover, several indirect relations and precedence relationships might coexist. Increasing public awareness about shipping emissions may directly influence the leading companies to take early practical action (Brauer & Khan, 2021; Dessens, Anger, Barker, & Pyle, 2014), which may lead to the development of green ammonia-fuelled propulsion systems. The complex relations depicted in these examples cause difficulty in perceiving antecedent factors.

Revealing antecedent factors and the structural relationships between success factors can help manage green ammonia adoption more efficiently and effectively by addressing antecedent factors and using limited resources more efficiently. Accordingly, our paper aims to identify and reveal the precedence relationships between critical success factors of green ammonia adoption. The depiction of structural relations between success factors can reveal those antecedent factors which can lead to the accomplishment of other factors. We use Interpretive structural modelling (ISM) and Cross-Impact Matrix Multiplication Applied to Classification (MICMAC) methods to reveal the structural relations between success factors.

This study contributes to the literature by being the first one, to the best of our knowledge, to empirically examine the judgement of experts regarding green ammonia adoption and reveal structural relationships between success factors for green ammonia adoption. Our study differs from earlier studies as it illustrates the precedence relations between critical sucess factors (CSFs) rather than simply measuring the importance of each CSFs. That is, our study has answered the question of "Which critical success factors take precedence in green ammonia adoption?". Cost, for instance, is considered a major factor in alternative fuel studies, the most important one in many, yet our results show a total of eight CSFs must be tackled and accomplished first for the cost issue to be resolved. The purpose of the study is not prioritising factors based on their importance levels or selecting an alternative fuel type. Results of our study demonstrate the structural relationships between CSFs which reveals precedence relations among success factors and illustrate antecedent factors. The study provides several policy and practical implications as scrutinising structural relations has enabled depicting a visual picture of steps required to be taken for green ammonia adoption.

2. Literature review

2.1. Ammonia as an alternative fuel in shipping

Ammonia is considered as one of the most prominent alternatives in the medium to long term (Wang et al., 2022; Xing, Stuart, Spence, & Chen, 2021). There are several reasons to support ammonia uptake. First, green ammonia has a slightly higher volumetric energy density than that of methanol and significantly higher than that of hydrogen. Hence it is more suitable for both deep-sea and short-sea journeys (Al-Enazi, Okonkwo, Bicer, & Al-Ansari, 2021), suggesting better storage medium on-board. Ammonia can be in liquid form under pressure at 0.8 MPa at 20 °C of temperature, or at atmospheric pressure at −33 °C, hence significantly less complicated in transport and storage (Al-Aboosi et al., 2021).

Second, ammonia is available for both combustion engines and fuel cells (Frattini et al., 2016). Although methanol has similar characteristics, ammonia is a more attractive option as it has 40% greater hydrogen than methanol (Giddey, Badwal, Munnings, & Dolan, 2017; McKinlay et al., 2021). Moreover, ammonia has a key advantage in terms of a mature and ready infrastructure for production, storage, and transportation because ammonia has long been used in fertiliser production (Al-Aboosi et al., 2021; Valera-Medina, Xiao, Owen-Jones, David, & Bowen, 2018). There are still adjustments needed for storing and distributing the bunker fuel of ammonia, the existing infrastructure and safety procedures in ammonia handling will limit the need for new infrastructure investment and training.

Finally, burning ammonia does not produce carbon dioxide. The studies that focus on life cycle assessment for alternative fuels (e.g. Bilgili, 2021; Zincir & Arslanoglu, 2024) reveal that green ammonia delivers a sustainable and favourable combustion performance, yet its production, conversion and safety should be improved.

Multi-criteria decision modelling (MCDM) studies were conducted for fuel selection in the shipping industries. For instance, Moshiul, Mohammad, and Hira (2023) conducted a study to prioritise alternative fuel selection aligned with the sustainability dimension using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method. Munim, Chowdhury, Tusher, and Notteboom (2023) carried out a study about prioritising alternative energy sources for sustainable shipping with Bayesian Best-Worst Method and the PROMETHEE-GAIA method after identifying nine criteria. Mollaoglu, Bucak, Demirel, and Balin (2023) performed TOPSIS analysis to evaluate various fuel alternatives for ship investment decisions in relation to the sustainability aspect. However, all research undertaken attempted to determine the criteria to prioritise when selecting alternative fuels. The literature is lacking in determining the structural relationships of success factors of alternative fuel adoption in shipping.

Considering several key opportunities and difficulties, green ammonia is chosen to be the focus of the paper. There are different approaches to synthesise ammonia. However, in this paper, only 'green ammonia', which is produced using CO2-free energy sources in the Haber-Bosch process, remains the focus when discussing ammonia. The other two types of ammonia - 'grey ammonia' and 'blue ammonia', whose production process still involves fossil-based feedstocks and energy, hence not entirely green fuels, will not be considered.

2.2. Critical success factors of green ammonia adoption in shipping

Despite the existence of some studies about fuels in shipping, the number of studies tackling the adoption of alternative fuels is limited. Only a few papers conduct empirical research with stakeholders to examine alternative fuels. Among them, Mäkitie et al. (2022) implemented a survey on Norwegian shipowners to investigate their adoption. Authors listed a total of nine barriers and eleven motivations for adoption to an alternative fuel. None of the empirical studies on fuel adoption has focused on green ammonia. Moreover, some of the factors debated in the industry such as carbon taxing and availability have not been examined in previous studies. Accordingly, our study has derived a total of 10 critical success factors by reviewing the literature, industry reports, and industry news. We now describe success factors.

2.2.1. Cost - reducing the cost of green ammonia

The cost plays a central role in adoption to any successful initiative like a new technology or more sustainable materials as energy cost accounts for more than 50% of the operating costs of a ship (Elgohary, Seddiek, & Salem, 2015). Thus, the cost reduction is a key factor in providing incentives for investment and adoption of an alternative energy (Acciaro, Hoffmann, & Eide, 2013). The cost of adoption does not only refer to the per-ton price of green ammonia, but also the investment cost for running green ammonia fuelled vessels. Norwegian shipowners, for instance, found investment cost as the most important barrier to adopt alternative fuels (Mäkitie et al., 2022).

The importance of cost reduction in alternative fuel adoption has been underlined by several studies. Rehmatulla and Smith (2015) underlined the importance of cost in low carbon energy adoption by indicating that energy costs can represent up to 70% of operating costs. Styhre and Winnes (2013) considered financial risks as an important barrier to the adoption of alternative fuel in shipping. Brauer and Khan (2021) found that freight transport stakeholders consider higher cost of biogas as the leading barrier for adoption. Christodoulou and Cullinane (2021) also documented high costs Stena Ferry Lines have faced in their ongoing decarbonisation journey. Similarly, Dahlgren, Kanda, and Anderberg (2022) revealed the high cost of biogas as one of the important barriers. Economic and financial concerns are also indicated as an important barrier among Greek shipping stakeholders to LNG adoption and electric energy.

Concerns of stakeholders about cost of alternative fuel adoption necessitates to reduce the cost of ammonia implementation in shipping. Green ammonia is expected to be more expensive than grey ammonia in the short term due to the current higher cost of renewable energy generation. According to Al-Aboosi et al. (2021), the cost of green ammonia production is expected to be competitive with other conventional sources of energy thanks to advanced technology, as the largest cost components of green ammonia production are electrolysis and renewable energy. The increase of R&D investment in ammonia technology is a necessity to cost reduction of implementing ammonia.

2.2.2. R&D - Increase of R&D in green ammonia

Green ammonia R&D comprises variables related to investments in research and new technologies, infrastructure, and specialised human resources needed for the energy implementation process (de Medeiros, Ribeiro, & Cortimiglia, 2014). Especially when there are still challenges in terms of safety assessment for ammonia-fuelled ships, technology maturity, and affordability of the implementation process, R&D plays a key role to its success in shipping.

The U.S. Department of Energy seeks improvements in catalysts, electrolysis and absorbents – as well as novel fuel cell technologies for ammonia. According to ShipInsight (2021), a group of 23 industry leaders in different sectors including energy, mining, chemical, shipping, bunkering, power utilities have set up a 'Joint Study' framework for improving ammonia R&D. Especially solid oxide electrolysis cell technology can streamline the electrolysis process. Therefore, it is believed to make the electrolysis much cheaper (Murray, 2020). Moreover, as ammonia is corrosive, more research in storage material and the design of marine fuel systems should be conducted (MAN Energy Solutions, 2019).

2.2.3. Safety regulations - Introduction of safety regulations for ammonia as fuel

There are studies in which concerns about its safety have been raised (Hansson, Brynolf, Fridell, & Lehtveer, 2020; Kim, Roh, Kim, & Chun, 2020; McKinlay et al., 2021). Ammonia is highly toxic to people as well as organisms living in the water. The toxicity of liquid ammonia is significantly higher than that is of diesel and methanol (Klerke, Christensen, Nørskov, & Vegge, 2008). Moreover, despite its low flammability, its container can explode when exposed to high heat. Thus, although there have been available safety protocols for ammonia as fertiliser, new safety regulations for ammonia as a marine fuel are required, considering its leakage possibility and toxicity. Safety protocols and regulations are vital for promoting public awareness of ammonia (MacFarlane et al., 2020; Morlanés et al., 2021). To achieve this goal, initial steps have been taken in industrial practices. The MotorShip (2019) reported that MAN Energy Solutions expect amendments on the International Gas Carrier Code to include ammonia as a ship fuel. In addition, classification rules have been developed based on existing rules for ammonia tankers to make sure that humans do not have direct contact with the substance (McKinlay et al., 2021).

2.2.4. Propulsion technology - Development of ammonia-fuelled propulsion

Optimising propulsion systems is one of the most necessary yet difficult steps in shipping decarbonisation (Blasco, Durán-Grados, Hampel, & Moreno-Gutiérrez, 2014; Dedes, Hudson, & Turnock, 2012), especially with a new alternative source of energy like ammonia. As Kim et al. (2020) investigated, approximately 83.7–92.1% of GHG emissions could be reduced if the ammonia-fuelled ship uses an appropriate propulsion system and fuel production method. Combustion engine propulsion and fuel cells are both options for ammonia (Hansson et al., 2020). There have been several projects focusing on the former. Some of the most significant ones are Caterpillar's patent for an ammonia-fuelled engine and ancillary systems (ShipInsight, 2019) and MAN Energy Solutions' project to commercialise two-stroke ammonia engines for container ships by 2024 (MAN Energy Solutions, 2019). These projects are expected to systematically develop the propulsion system.

Another promising option is using ammonia in a fuel cell system. Although this technology is now dominated by hydrogen, Kim et al. (2020) note that ammonia-fuelled power systems will arise in the next years. One of the most noticeable projects is that a Norwegian supply vessel is retrofitted to be powered with ammonia fuel cell. This project, which aims to use a direct ammonia solid oxide fuel cell, has received significant funding from the EU (Brown, 2020). Specifically, the project has changed the view of the leaders of the hydrogen community: instead of considering ammonia as a hydrogen competitor, it is now seen as a hydrogen carrier, which enables much more opportunities for ammonia. Although the fuel cells still cost much higher compared to internal combustion engines, research efforts have been focused on generating lower-cost hydrogen from ammonia.

2.2.5. Port infrastructure - Development of port infrastructure for green ammonia supply and delivery

Ports actively manage energy as energy is required for powering ships and any cargo handling process (Iris & Lam, 2021). Moreover, as the energy transition process is still at its early stage, ports also play the role of laboratories to test new technologies. The International Energy Agency reported that ports can also serve as industrial hubs for hydrogen and ammonia production for the shipping, rail and hinterland industry, as well as for refuelling ships (Washington, 2021). Iris and Lam (2019) noted that developing port infrastructure is crucial for safety, security, and market issues. Infrastructure development has been the focus of many ports worldwide to support the adoption of alternative sources of energy (Foretich, Zaimes, Hawkins, & Newes, 2021). Noticeably, the Port of Rotterdam intends to support an import terminal for up to 2,5 million tons of green ammonia per year from 2024 (*Alliance for green hydrogen production and import*, 2021). Similarly, Abu Dhabi's Khalifa port is developing a proposal for a green ammonia export facility, turning the port into an ammonia hub (The Maritime Executive, 2021). To achieve this goal, a storage facility will be installed to store a large volume of ammonia.

2.2.6. Availability - Maximising availability of green ammonia supply

Producing ammonia from small to utility scale is crucial when it is to be the main fuel in short and deep-sea shipping (Valera-Medina et al., 2018). Grey ammonia which constitutes a large percent of current supply generates significant CO2 due to the steam reformation process of methane (Tullo, 2021). Blue ammonia can reduce climate impact compared to grey ammonia as the emitted CO2 can be captured and injected into oil fields for enhanced oil recovery.

In the long-term, net-zero green ammonia from renewable energy is main target (Haskell, 2021). Green ammonia might be very costly in the short term, prices can be reduced with increasing production capacities. Fasihi, Weiss, Savolainen, and Breyer (2021) have suggested that green ammonia can be produced in a hybrid PV-wind power plant. From 2030, green ammonia can be cost-competitive, or can even substitute grey ammonia as the average cost of this type of ammonia is 300–350 €/t. In addition, a lot of large projects have been unveiled in Norway, Saudi Arabia, the US, and Red Sea coast, promising to produce up to 1.2 million t per year of ammonia in 2025 (Tullo, 2021). Note that, in a complete analysis, all storage and transportation costs and efficiencies should be considered in the cost analysis.

2.2.7. Stakeholder support - Support from and collaboration with stakeholders

Stakeholders play a vital role in the successful adoption to sustainable shipping practices (Tran, Yuen, Li, Balci, & Ma, 2020). The shipping industry ecosystem involves a vast number of stakeholders - encompassing, but not limited to, shipowners, charterers, cargo owners, NGOs, bunker suppliers, and port state – that the collaboration between them are essential for cleaner energy adoptions. Several cleaner fuel adoption studies also underline the importance of stakeholder support and collaboration. Sideri, Papoutsidakis, Lilas, Nikitakos, and Papachristos (2021) and Pfoser, Aschauer, Simmer, and Schauer (2016) adopted a stakeholder approach to study LNG and electricity as a fuel in the shipping. Dahlgren et al. (2022) indicated stakeholder requirements as an important driver in biofuel adoption in Sweden.

Besides academia, the industry members have also voiced the importance of collaboration for maritime decarbonisation. Directors in DNV, a leading class society, have particularly underlined the necessity of stakeholder collaboration for cleaner fuel adoption (DNV GL, 2019). The shipping industry demonstrates several examples of collaboration for decarbonising shipping through green ammonia. The Nordic Green Ammonia Powered Ships initiative is an example of collaboration as it involves stakeholders from finance, ship operation, marine engine, shipbuilding, classification, energy supplier, research institutes, and NGOs (Nordic Innovation, 2022). This project aligns with the recommendation of Parviainen, Lehikoinen, Kuikka, and Haapasaari (2018) who suggest that the collaboration should happen between different levels of partners for sustainable shipping. The impact of collaboration is witnessed in one of the first full scale ammonia engine test which was actualised by collaborative work of private companies Wärtsilä, Knutsen Shipping, and Kelson, the Sustainable Energy Catapult Centre, and Norwegian Research Council (Wärtsilä, 2020). Another cross-industry example is among Mabari Shipbuilding, MAN Energy Solutions, Mitsui, ClassNK, and ITOCHU in which companies collaborate on developing ship propulsion with ammonia (Taylor, 2020).

2.2.8. Carbon tax - Imposition of carbon taxes

The implementation of decarbonisation measures can be costly and complicated. Thus, consistent incentives will make it more attractive for ship operators to participate in decarbonisation schemes (Becqué, Fung, & Zhu, 2018; Heitmann & Peterson, 2014). Decarbonisation also requires financial resources for R&D, infrastructure and superstructure, and green investments. This calls for the imposition of carbon taxes and/or cap-and-trade mechanisms which can assist the shipping industry to decarbonise operations. As Pearce (1991) stated, carbon taxes act as "a continuous incentive to adopt ever cleaner technology and energy conservation" (p. 942). The imposition of carbon tax can contribute in different ways. The first expected effect is that the price increase in fossil fuels will have a deterrent effect on fossil fuel use and encourage more investment on cleaner technologies. For instance, Yue et al. (2022) conducted an econometric analysis and found that carbon pricing positively influences the adoption of cleaner fuel technologies and renewable energy. Lundgren, Marklund, Samakovlis, and Zhou (2015) also found that an increase in fossil fuel price encourages greener technology development. The literature also supports that bunker pricing can support the decarbonisation of shipping (Lagouvardou, Psaraftis, & Zis, 2022). In practice, International Chamber of Commerce is preparing a proposition of USD 5 billion fund for R&D, which is planned to be generated by a mandatory levy of $2 per ton on marine fuel.

Besides carbon tax's deterrent effect on fossil fuel usage, it can also create essential financial resources for R&D for net-zero fuels such as green ammonia. The revenue generation plays a key role in developing countries and smaller-scale ship operating organisations that may lack required resources for investing in greener energy (Dominioni, Englert, Salgmann, & Brown, 2022). The distribution of carbon revenues to smaller companies can attract support from wider stakeholders as well. The revenue generation is also expected to improve the maritime infrastructure for the distribution of greener energy (Dominioni et al., 2022). Carbon tax is also believed to increase the awareness about shipping emissions among consumers (Sørås, 2021).

It is acknowledged that imposition of carbon tax is disputed as it is claimed that it might further increase freight rates and put more financial burden on customers (SP Global, 2021). The discussion of whether and how carbon tax should be applied is beyond the scope of this study. Nonetheless, the incentive has been backed by leading international organisations including International Chamber of Shipping, World Shipping Council, and Cruise Lines International Association (Josephs, 2021). A working paper International Monetary Fund also supports the implementation of carbon taxes for decarbonising shipping (Parry, Heine, Kizzier, & Smith, 2018). The World Bank also issued a technical paper regarding how carbon taxing should be implemented (Dominioni et al., 2022). Japan and the EU have already proposed carbon taxing schemes for shipping as well. Particularly, the European

Union has decided to include shipping in the Emissions Trading Scheme (EU ETS), a system for cap-and-trade for emission control and carbon market management (Wang, Zhen, Psaraftis, & Yan, 2021).

2.2.9. Public awareness - Increase of social awareness about shipping emissions

The literature has shown that the lack of social awareness is a major reason for limited green practices (Biresselioglu, Demir, Demirbag Kaplan, & Solak, 2020; Oberhofer & Dieplinger, 2014), and the shipping industry is no exception. Raising environmental concerns plays a vital role in supporting policy regarding the deployment of marine renewable energy (Potts, Pita, O'Higgins, & Mee, 2016). Serra and Fancello (2020) identified social pressures and ecological awareness as one of the key drivers for the shipping industry to take decarbonisation efforts. Brauer and Khan (2021) stressed the importance of consumer influence on the successful diffusion of cleaner marine fuels, as evidenced in other sustainability measures of global firms (Chen, Fei, & Wan, 2019; Cullinane & Cullinane, 2013; Venturini, Iris, Kontovas, & Larsen, 2017).

The recent developments mirror findings in the literature regarding the influence of consumers in the decarbonisation efforts. Recently, consumer and retail brands established heavy pressure on shipping industry to reduce GHG emissions as part of their Net-Zero pledges made to consumers. For instance, global brands such as Amazon and Unilever pledged to use maritime shipping services only working with Net-Zero fuels after 2040 (Thomas, 2021). The consumer pressure following social awareness can also lead to collaboration between stakeholders such as CMA-CGM and IKEA trying bio-fuel shipment after a collaborative effort. The increasing one-stop logistics integration efforts of container lines push them more towards direct relations with consumers as well. This is evident in practice as CMA-CGM and Maersk, which invests heavily for logistics integration (Paridaens & Notteboom, 2022), are also taking proactive actions to decarbonise their fleet.

2.2.10. Early adopters - Early practical actions by leading shipping companies

Similar to other industries, the lack of early adopters can hinder the innovation in the shipping (Balci & Surucu-Balci, 2021). Early adopters play a vital role in alternative fuels uptake as early actions taken by leading shipping companies can galvanise the industry into action regarding technology improvement, infrastructure investment, and better understanding of how alternative fuels can work in practice (Mäkitie et al., 2022). The early adoption by leading firms can also inspire the rest of the value chain to take action (Zhen, Wu, Wang, & Laporte, 2020; Madsen, 2021). Lister (2015) documented private green shipping initiatives and underlined their roles in influencing global practices especially considering the lack of green regulations. Lister (2015) also stated the effect of private green actions on international policy and regulations building. The institutional isomorphism in supply chains – which causes firms to change their organisational practices in alignment with their partners such as adopting a new technology (Lai, Wong, & Cheng, 2006) – also underpins the effect of leading companies on green fuel adoption in shipping.

3. Methodology

This study adopted a three-step research process to meet the research aim (see Fig. 1 for the details of research process). First, a literature review was conducted to identify green ammonia adoption success factors. Next, to finalise the list of factors, a total of six interviews were completed with experts who are knowledgeable about green ammonia adoption (see information about interviewees in Appendix C). Third, an ISM survey is completed by 48 experts about green fuels in shipping to reveal relationships between success factors (see the survey in Appendix A). Analyses in this study (ISM and MICMAC) are conducted based on the surveys with 48 experts.

The ISM survey consisted of two parts. The first part included questions related to experts' demographics, whereas the second part asked about the ISM questionnaire. Experts were asked to identify relationships between CSFs through pairwise comparisons (A total of 45 comparisons for 10 CSFs), as shown in Appendix A. That is, experts were asked to determine the relationship direction between two CSFs in four options (i.e., Factor A influences Factor B, Factor B influences Factor A, both influence each other, and do not influence each other).

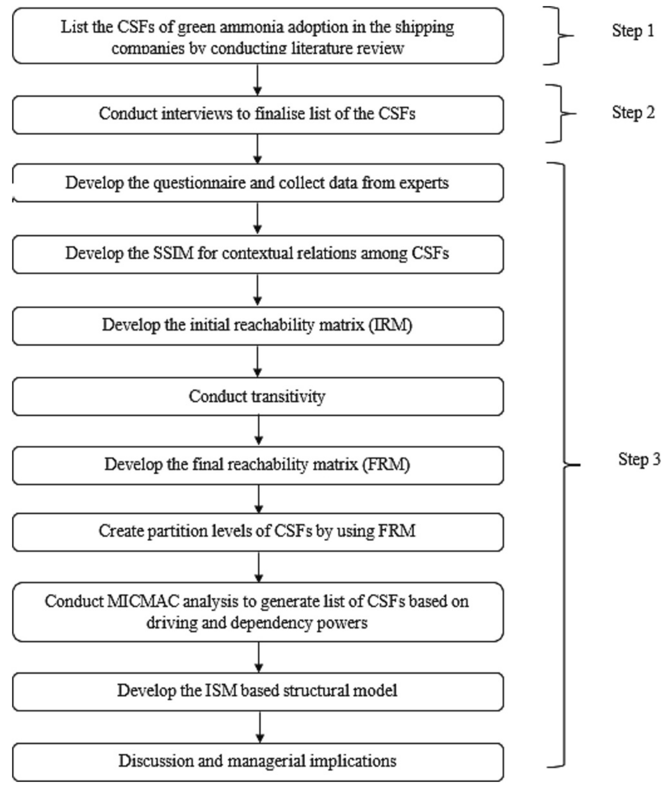

Fig. 1. Research process.

We implemented a judgmental sampling approach – a type of non-probability sampling – to ensure that experts are knowledgeable about alternative fuels in shipping. The experts are chosen on the social network LinkedIn based on their profiles, shares, and interactions regarding green ammonia and alternative fuels in shipping. “Green ammonia” and “shipping or maritime” are used as keywords in the search. The LinkedIn network has been proven effective and reliable in collecting data from experts, especially in the supply chain industry, thanks to its professional logistics-oriented profile (Kaliszewski, Kozłowski, Dąbrowski, & Klimek, 2021). A total of 48 experts completed the survey, which is deemed satisfactory considering limited number of experts knowledgeable about green ammonia. Our sample also illustrates the representation of different stakeholders in the industry. More than 10 different stakeholder categories, including shipowners, class society, governmental bodies, and engine builders, are present in our sample (Table 1). As shown in Table 1, most respondents are in managerial and engineering positions in their organisations and knowledgeable about alternative fuels.

3.1. ISM methodology and process

ISM converts unclear and complex relationships between variables into distinguishable and straightforward precedence models (Sushil., 2012). The main idea of ISM is to deconstruct a complex system into various components, build a multi-level structural model, and provide knowledge of tough situations to provide a problem-solving method (Zekhnini, Cherrafi, Bouhaddou, Benghabrit, & Belhadi, 2022). ISM is the process of transforming imprecise, poorly articulated mental models

Table 1
Demographics of experts.

Profile	Frequency	Percentage
Organisation of respondent		
Container line / Shipowner / Operator	5	16.7
Transport Intermediaries	3	6.3
Port/Terminal	4	8.3
Energy producer / bunker supplier	8	16.7
Class society	4	8.3
University	7	8.3
Manufacturer / shipper / cargo owner	3	6.3
Clean energy consultancy	4	8.3
Shipbuilding / Marine Engine	4	8.3
Governmental organisation / NGO	3	6.3
Others	3	6.3
Experience of respondent		
1–3 years	3	6.3
4–6 years	7	14.6
7–10 years	9	18.8
11–14 years	13	27.1
15 and over	16	33.3
Age of respondent		
18–25 years old	3	6.3
26–34 years old	9	18.8
35–44 years old	17	35.4
45–54 years old	12	25.0
55 and more	7	14.6
Region of respondent		
Africa	2	4.2
America	10	20.8
Asia	12	25.0
Europe	17	35.4
Australia / Oceania	4	8.3
Middle East	3	6.3

The expert opinions were then organised hierarchically and logically using ISM and MICMAC. The details of the ISM process are explained in the next section.

of systems into observable, well-defined models (Attri, Dev, & Sharma, 2013). It is a systematic and collaborative approach which enables the investigation of relations between variables.

ISM uses complex equation systems to create binary links to reveal interconnections between variables (Rana, Barnard, Baabdullah, Rees, & Roderick, 2019). ISM is based on structural modelling (SM), which describes formation rather than quantification and expresses a problem geometrically rather than algebraically (Lendaris, 1980). It is a methodology that focuses on choosing model components and explicitly characterising their relationship to clarify the framework of a complex subject, system, or body of knowledge (McLean & Shepherd, 1976). This indicates that the model defining the linkages between the variables in SM takes a qualitative rather than quantitative form in graphs and interconnections (Sorooshian, Tavana, & Ribeiro-Navarrete, 2023).

However, the ISM method has been criticised that the identified relations might not be of the same strength (Khan & Haleem, 2015); therefore, to enable robust results, we conjoined ISM with MICMAC analysis (Balci & Surucu-Balci, 2021). MICMAC analysis classifies variables with respect to their driving and dependence power. Conjoined ISM with MICMAC analysis is better suited for assessing contextual relationships between variables whose internal links have not been previously investigated in the literature (Mangla et al., 2018). Furthermore, conjoined ISM with MICMAC is proven to be a suitable modelling approach for analysing the influence of one variable on another variable relevant to a problem or an issue (Raut, Narkhede, & Gardas, 2017). The suitability of these methods for cleaner vehicles and fuels is also discussed in the literature (see e.g. Palit, Bari, & Karmaker, 2022).

Different methods, such as the Analytical Hierarchy Process (AHP), Analytical Network Process (ANP) or TOPSIS could be used to find the hierarchical structures. Creating a model with the stated techniques necessitates the dominant degree of interactions between the two variables, whereas ISM does not. Instead, ISM necessitates interrelationships between variables to construct a model, which is also consistent with the aim of this study. As a result, the model generated with ISM may produce better results compared to existing MCDM techniques (Gardas, Raut, & Narkhede, 2017). Furthermore, ISM can show dynamic complexities, whereas AHP or ANP are less capable of capturing dynamic behaviours (Magalhaes, Ferreira, & Cristovao, 2021).

The ISM-MICMAC analysis includes the following steps (Raut et al., 2017): (1) defining the variables which are related to the research question by using expert judgments and literature review; (2) establishing contextual relationships between variables by collecting data and generating a SSIM via pairwise comparisons; (3) obtaining an IRM utilising SSIM; (4) amending IRM to form a final reachability matrix by utilising transitivity relations between variables (Balci & Surucu-Balci, 2021; Rana et al., 2019); (5) creating partition levels based on similarities of reachability and intersections sets; (6) calculating driving and dependency power of each variable using rows and columns of FRM and forming FRM hierarchy via reachability and antecedent sets; (7) performing MICMAC analysis to generate a list of variables using the calculated driving power (DRP) and dependency powers (DNP). As a result, four groups can be employed (dependent, linkage, drivers and autonomous) to base expert judgments (Sindhwani & Malhotra, 2017); (8) forming digraphs for variables stated in FRM to visualise variable relationships; (9) creating an ISM-based model utilising the reachability and intersection datasets to obtain the outcomes.

4. ISM – MICMAC analysis and results

4.1. Self-structured interaction matrix (SSIM)

The SSIM is obtained based on the interrelationships, which were determined by the experts, among CSFs. The interrelationships are as follows. V means CSF *i* influences CSF *j*. A means CSF *j* influence CSF *i*. X means CSF *i* and *j* influence each other. O means CSF *i* and *j* do not affect each other (Balci & Surucu-Balci, 2021; Rana et al., 2019). Each expert has their own opinion and can assess the relationships differently, resulting in recording different letters to each relationship between the two CSFs. Therefore, we followed Shen, Song, Wu, Liao, and Zhang (2016)'s rule of 'minority gives way to the majority'; while creating contextual relationships between CSFs. Table 2 shows the SSIM results. Appendix B illustrates frequencies and percentages of relationship directions for each pairwise comparison of CSFs. Appendix B is used to determine the relationship direction between pairs of success factors.

4.2. Development of IRM

The next step of ISM methodology is forming IRM. IRM is created based on the transforming V, A, X and O symbols into binary values (0 and 1). We adopted the following method for conversion (Mangla et al., 2018; Rana et al., 2019). If the expert selected V for the *(i, j)* input, the input in the reachability matrix is 1, and the *(j,i)* input is 0. If A is selected for the *(i,j)* input, then the *(i,j)* input in the reachability matrix is 0, and *(j, i)* is 1. If X is selected for the *(i, j)* input in the SSIM, the *(i, j)* input in the reachability matrix is 1 and (j, i) input is also 1. If the *(i, j)* input in the SSIM is O, both *(i, j)* and *(j, i)* inputs in the reachability matrix is 0. Table 3 shows the IRM, using the SSIM.

4.3. Development of FRM

The rule of transitivity should be employed to create an FRM table. The transitivity rule assumes that if CSF *i* is related to CSF *j* and *j* is related to CSF *k*; then CSF *i* is also related to CSF *k*. After checking for the transitivity, the newly obtained matrix is called FRM. Table 4 shows the FRM for this study.

Table 2
SSIM.

CSF	Early Adopters	Public Awareness on Emissions	Carbon Tax	Stakeholder Support	Availability	Port Infrastructure	Propulsion Technology	Safety Regulations	R&D
Cost	O	O	A	A	A	V	A	O	A
R&D	A	A	A	A	V	V	V	X	
Safety Regulations	A	A	O	A	O	V	V		
Propulsion Technology	A	A	A	A	X	V			
Port Infrastructure	A	O	A	A	O				
Availability	A	O	A	A					
Stakeholder Support	X	A	X						
Carbon Tax	A	X							
Public Awareness on Emissions	X								

Table 3
IRM.

CSFs	Cost	R&D	Safety Regulations	Propulsion Technology	Port Infrastructure	Availability	Stakeholder Support	Carbon Tax	Public Awareness on Emissions	Early Adopters
Cost	1	0	0	0	1	0	0	0	0	0
R&D	1	1	1	1	1	1	0	0	0	0
Safety Regulations	0	1	1	1	1	0	0	0	0	0
Propulsion Technology	1	0	0	1	1	1	0	0	0	0
Port Infrastructure	0	0	0	0	1	0	0	0	0	0
Availability	1	0	0	1	0	1	0	0	0	0
Stakeholder Support	1	1	1	1	1	1	1	1	0	1
Carbon Tax	1	1	0	1	1	1	1	1	1	0
Public Awareness on Emissions	0	1	1	1	0	0	1	1	1	1
Early Adopters	0	1	1	1	1	1	1	1	1	1

Table 4
FRM.

CSFs	Cost	R&D	Safety Regulations	Propulsion Technology	Port Infrastructure	Availability	Stakeholder Support	Carbon Tax	Public Awareness on Emissions	Early Adopters	DRP
Cost	1	0	0	0	1	0	0	0	0	0	2
R&D	1	1	1	1	1	1	0	0	0	0	6
Safety Regulations	1[a]	1	1	1	1	1[a]	0	0	0	0	6
Propulsion Technology	1	0	0	1	1	1	0	0	0	0	4
Port Infrastructure	0	0	0	0	1	0	0	0	0	0	1
Availability	1	0	0	1	1[a]	1	0	0	0	0	4
Stakeholder Support	1	1	1	1	1	1	1	1	1[a]	1	10
Carbon Tax	1	1	1[a]	1	1	1	1	1	1	1[a]	10
Public Awareness on Emissions	1[a]	1	1	1	1[a]	1[a]	1	1	1	1	10
Early Adopters	1[a]	1	1	1	1	1	1	1	1	1	10
DNP	8	6	6	8	10	8	4	4	4	4	

[a] Adding transitivity.

4.4. Partitioning of levels

The next step is breaking down the FRM considering the significance of forming a hierarchical structure utilising reachability, antecedent and intersection sets. The reachability set encompasses the CSFs it impacts, while the antecedent set includes the CSFs and other CSFs that affect this CSF. The intersection set is formed by overlapping the reachability and antecedent sets and is named Level I. Identification of the intersection set will be followed by removing the set and repeating the process until all CSFs are tackled. Table 5 shows the results of level partitioning.

According to Table 5, five levels are created with the level partitioning. Level I includes *'Port infrastructure - Development of port infrastructure for ammonia supply and delivery (E)'*. Level II consists of *'Cost - Reducing the cost of green ammonia (A)'*. *'Propulsion systems - Development of ammonia-fuelled propulsion systems (D)'* and *'Availability - Maximising availability of ammonia supply (F)'* establish Level III. Level IV involves *'R&D - Increase of R&D in green ammonia (B)'* and *'Safety regulations - Introduction of safety regulations for ammonia as a fuel (C)'*. Level V encompasses *'Stakeholder support - Support from and collaboration with stakeholders (G)'*, *'Carbon tax - Imposition of carbon taxes (H)'*, *'Public awareness - Increase of social awareness about shipping emissions (I)'* and *'Early adopters - Practical actions from leading shipping companies (J)'*.

Table 5
Results of level partitioning.

CSFs	Reachability Set	Antecedent Set	Intersection Set	Level
Cost	1,5	1,2,3,4,6,7,8,9,10	1	II
R&D	1,2,3,4,5,6	2,3,7,8,9,10	2,3	IV
Safety Regulations	1,2,3,4,5,6	2,3,7,8,9,10	2,3	IV
Propulsion Technology	1,4,5,6	2,3,4,6,7,8,9,10	4,6	III
Port Infrastructure	5	1,2,3,4,5,6,7,8,9,10	5	I
Availability	1,4,5,6,	2,3,4,6,7,8,9,10	4,6	III
Stakeholder Support	1,2,3,4,5,6,7,8,9,10	7,8,9,10	7,8,9,10	V
Carbon Tax	1,2,3,4,5,6,7,8,9,10	7,8,9,10	7,8,9,10	V
Public Awareness on Emissions	1,2,3,4,5,6,7,8,9,10	7,8,9,10	7,8,9,10	V
Early Adopters	1,2,3,4,5,6,7,8,9,10	7,8,9,10	7,8,9,10	V

4.5. MICMAC analysis and results

MICMAC analysis helps to classify the scope of each CSF indirectly. The MICMAC analysis aims to calculate the DNP and DRP of the CSFs. The FRM is used to calculate DNP and DRP. DNP is calculated as the summation of the columns, while DRP is the summation of rows. DNP and DRP are presented in Table 4. The DRP and DNP are used to identify the positions of CSFs among the quadrants in the MICMAC matrix. The DRP and DNP are used as coordinates in the MICMAC diagram. Fig. 2 shows the quadrants and the MICMAC diagram for this study. The four quadrants are (Balci & Surucu-Balci, 2021): Independent, Dependent, Autonomous and Linkage.

Autonomous: These CSFs have both low DNP and DRP. These CSFs have the lowest effect and influence to other CSFs. Also, these CSFs have restricted relations with other variables in the ISM model.

Independent: These CSFs have low DNP and high DRP and can be considered essential factors that impel other factors up in the hierarchical model. These CSFs are mostly located at the bottom of the ISM model.

Linkage: These CSFs have both strong DNP and DRP, and they are considered unstable because any actions taken for these CSFs will lead to a reciprocal reaction, influencing other CSFs.

Dependent: These CSFs have strong DNP and weak DRP, and generally, they are driven by other CSFs. These CSFs tend to be located at the top of the ISM model.

Most CSFs are within the Independent and Dependent quadrants based on Fig. 2. This pinpoints that most of the CSFs have high DRP and DNP. *'Stakeholder support (G)'*, *'Carbon tax (H)'*, *'Public awareness (I)'* and *'Early adopters (J)'* are classified as Independent in this study. These CSFs necessitate consideration because they are the root cause, and precedence of the other CSFs. CSFs with high DRP need to be tackled because they influence other CSFs. Because of the fact that the presence of these CSFs can also empower the creation of other CSFs, which will have an impact on easing the green ammonia adoption.

Two CSFs are categorised as Linkage, *'R&D (B)'* and *'Safety regulations (C)'*. According to the characteristics of the Linkage CSFs, they need to be monitored closely because any insufficiency in these CSFs can lead to a domino effect and cause other CSFs to regress since they provide many links between CSFs. No Autonomous CSFs were identified in this study, meaning that all of the discovered CSFs affect green ammonia adoption in the shipping industry.

Four CSFs, *'Port infrastructure (E)'*, *'Cost (A)'*, *'Propulsion systems (D)'* and *'Availability (F)'* are categorised as Dependent. These CSFs are considered critical CSFs because the facilitating role of these CSFs to ensure green ammonia adoption in the shipping industry depends on the existence of other CSFs.

4.6. CSFs relationship framework based on ISM and MICMAC results

As the last step, we employ FRM to establish the ISM model of CSFs in green ammonia adoption in shipping, shown in Fig. 3. The relationship between success factors is represented in the Fig. 3. The level of CSF is determined considering DRP and DNP. The figure is connected to the ISM and MICMAC results based on the 45 pairwise comparisons asked in

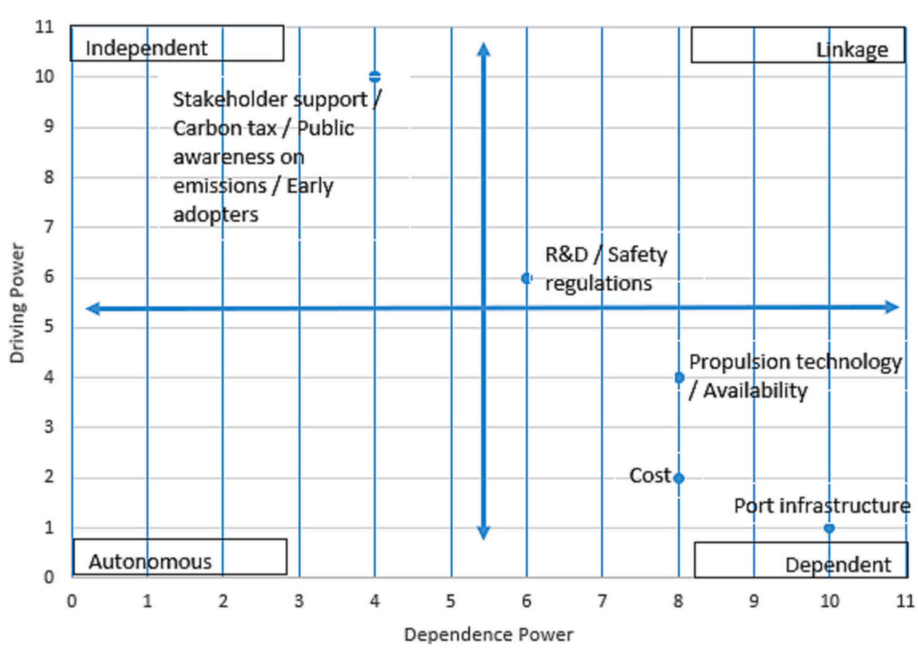

Fig. 2. MICMAC diagram.

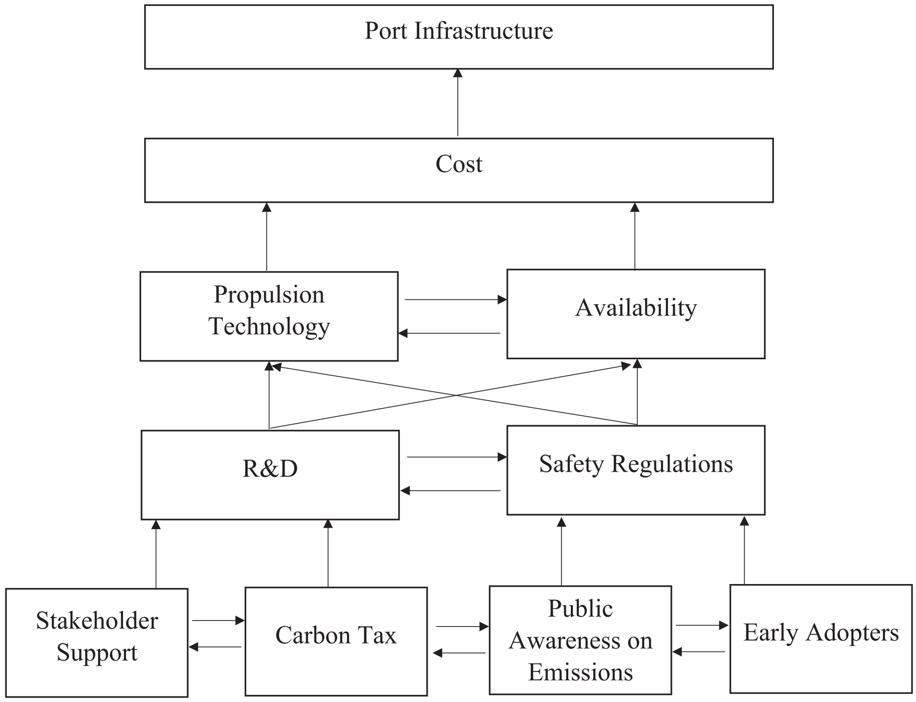

Fig. 3. CSFs Relationship Framework for green ammonia adoption in the shipping industry. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the survey.

The bottom level of the digraph contains four CSFs, *'Stakeholder support (G)', 'Carbon tax (H)', 'Public awareness on emissions (I)'* and *'Early adopters (J)'* as the result of Level V partitioning. The positioning of the CSFs is also verified with the MICMAC analysis. Based on the MICMAC analysis results, these four CSFs are classified as independent and have the highest DRP, and these variables to affect other variables. According to ISM and MICMAC results, these four variables are acknowledged as the antecedents of green ammonia adoption because they are the underlying CSFs to the successful green ammonia adoption in shipping.

The fourth level of the figure has two variables: *'R&D (B)'* and *'Safety Regulations (C)',* which is the outcome of Level IV partitioning. According to MICMAC analysis, these CSFs are classified as Linkage and act as a bridge between the dependent and independent variables with a certain level of DRP and DNP. The CSFs in the fourth level can be considered foremost transition CSFs because, without the antecedents in place, the foremost transition CSFs will be unable to function. Yet, their absence will significantly impact the adoption of green ammonia in the shipping industry.

According to partitioning level results, the third level of the figure includes two CSFs, *'Propulsion technology (D)'* and *'Availability (F),* as the dependent variable has both DRP and DNP. Level three CSFs are named secondary (second-degree) transition CSFs. The secondary transition CSFs will be required once the antecedents and foremost transition CSFs are in place.

The second level of the digraph also has one CSF, *'Cost (A)'*, filtered out from Level II partitioning. Furthermore, the MICMAC analysis also legitimises the partitioning results as a solid dependent variable. The cost is classified as third-degree transition CSFs. Once the antecedents, foremost transition and secondary transition CSFs are in place, the third-degree transition CSFs will be necessary.

The top level of the figure consists of one CSF: *'Port infrastructure (E)'*. This CSF is on the top of the model because it is identified as Level I in the level partitioning. The result is also supported by MICMAC analysis since this CSF is classified as dependent, with the highest value for DNP and the lowest value for DRP. Port infrastructure is identified as the consequent CFS. The CSF's incidence is reliant on all other CSFs that occur.

5. Conclusion and discussion

Green ammonia draws the attention of shipping stakeholders as a viable alternative fuel to achieve Net-Zero emission targets. It offers considerable advantages compared to its alternatives thanks to its high storage density, zero carbon content, and existing transport network of ammonia. Many industrial reports predict green ammonia to be a major Net-Zero fuel in maritime transport by 2040–2050. However, significant barriers also exist for industry-level green ammonia adoption including lack of regulations for ammonia as a marine fuel, the need for ammonia-powered engines, and insufficient and/or expensive renewable energy production. Ultimately, the successful adoption of green ammonia depends on several factors, and policy makers and practitioners should start working on these factors (Ash & Scarbrough, 2019). Our study aims to reveal the structural and precedence relationship between those CSFs to determine a roadmap.

This study identifies a total of 10 success factors of green ammonia adoption in the maritime supply chain and reveals the structural and precedence relations between them through conducting ISM and MICMAC analyses based on a total of 48 responses from industry experts. Our analysis helps uncover the most pivotal CSFs of green ammonia by illustrating how factors influence each other and revealing root and linkage factors which help allow the implementation of dependent factors. Our research does not show prioritisation of factors, but instead illustrates precedence relations to manage decarbonisation resources more effectively. It shows that success of dependent variables such as port infrastructure, cost, availability of fuels, and propulsion technology developments depend on linkage and antecedent factors such as stakeholder support, carbon taxation, and R&D.

Level 5 factors of the ISM analysis indicate that the most fundamental success factors of green ammonia adoption are stakeholder support, imposition of carbon taxes for decarbonisation, increase of public awareness about shipping emissions, and early practical actions from leading companies. MICMAC analysis also indicates these four variables as independent variables with the least dependencies on the other six variables. This result is parallel to the qualitative findings of Brauer and Khan (2021), who found regulations play a decisive role in the adoption of Biogas. The fundamental role of social awareness and stakeholder support are somewhat supported by Hessevik (2022), who considered customer demand as a main driver of decarbonisation in shipping.

Level 5 factors are antecedent CSFs that affect successful execution of factors at lower levels. Variables at Level 5 directly or indirectly influence each other too. It is quite relevant for these factors to be positioned at Level 5 as all four CSFs play an antecedent role that triggers the accomplishment of other CSFs. For instance, increasing public awareness about shipping emissions can cause more pressure on supply chains, governments, and other stakeholders to collaborate and channel their efforts for forming necessary regulations, increasing the R&D investments, and availability of supply. Similarly, supporting the argument of Lister (2015), early large-scale adopters can lead to actions in government regulations and even investment support, as in the case of public-private collaboration between Maersk and the Egyptian government for green fuel production.

The complex structure of green ammonia adoption also justifies why the level 5 the ISM model involves a relatively higher number of factors considering other ISM studies in similar contexts (Palit et al., 2022). Green ammonia adoption involves different complexities, such as safety regulations, engine improvements (such as dual-fuel engines), capacity, and technology improvements in renewable energies. These complexities compel a pressing action on several fundamental success factors. The order of levels and structural relations in the ISM also make sense. For instance, support from stakeholders and carbon taxing will provide sufficient resources for increasing R&D in green ammonia, which will trigger the development of ammonia-fuelled propulsion systems. The development of the propulsion system can reduce the cost of operating with green ammonia fuel, which eventually increases the demand for the fuel and causes the development of port infrastructure.

Level 4 factors, which are named as foremost transition CSFs, play a linkage role between antecedent and dependent factors, which is also relevant in the practical sense as these R&D investments and safety regulations are required first for achieving the development of engines, maximising the availability of green ammonia supply, and then eventually a reduction in the cost of running vessels with green ammonia. Unburned ammonia can be toxic when inhaled, thus it is not surprising that R&D facilities and safety regulations are found as linkage variables. Also, green ammonia requires renewable energy for production and more R&D is essential for more efficient and cost-effective solutions.

The ISM-MICMAC analyses illustrated the cost of ammonia as a dependent factor (third-degree transition CSF), and it is on the top of the ISM figure, just under the development of port infrastructure criterion (consequent CSF). This result shows that the cost of green ammonia is not a fundamental barrier, but it is mostly dependent on other antecedents. This somewhat contradicts some of the previous publications like Prussi, Scarlat, Acciaro, and Kosmas (2021), who claimed cost to be the most fundamental factor in alternative fuel adoption. This study also acknowledges the significance of the cost for adopting green ammonia, yet we claim it is just the tip of an iceberg. The fact that our study focuses on green ammonia may also provide different results as the cost reduction of green ammonia involves different cost aspects, such as the renewable energy costs, cost-effective engine technology, and efficient storage and bunkering.

The development of port infrastructure for supply and delivery is positioned at Level 1 (consequent CSF) because green port infrastructure investments are very costly and difficult to reverse due to limited space availability and construction challenges (Iris & Lam, 2019). The industry needs to be convinced first that ammonia can be a viable green fuel option with its availability, cost, technology, and regulations so that such significant port investments can be initiated. This result requires special attention as the bunkering infrastructure of green ammonia is not as developed as its counterparts, such as methanol (Foretich et al., 2021).

While the relationship framework (Fig. 3) we created based on ISM and MICMAC analyses illustrates antecedents and dependent factors of CSFs, it should be noted that these factors might need to be addressed concurrently. For instance, although carbon taxing is one of the antecedents of R&D, our results do not suggest policy makers to focus on only carbon taxing first and overlook R&D. Policy makers and relevant stakeholder can address both concurrently, yet our results suggest carbon taxing will help increasing R&D facilities for green ammonia adoption.

5.1. Theoretical contributions

This paper contributes to the literature in several ways. This would be the first study, as far as we know, to conduct empirical work and apply ISM and MICMAC methods for the barriers in green energy adoption. The examination of structural relationships between barriers is another main contribution. A total of ten CSFs are synthesised through a comprehensive review of existing literature, industrial commentaries, and expert consultations. The systematic approach has produced a comprehensive list of success factors of green ammonia adoption. Most existing studies are concerned with economic and environmental factors regarding the implementation of ammonia (Inal et al., 2022). Those studies significantly contribute by clarifying the environmental and technical requirements of successful implementation. However, green ammonia adoption is a complex one, compelling a more comprehensive evaluation of other factors as well. Our comprehensive list does not only contribute to green ammonia adoption but also other alternative fuels in the shipping industry. Moreover, CSFs identified in this study can be applied in other modes of freight and generic logistics decarbonisation following fuel-specific or industry-specific modifications.

In terms of methodology, to the best knowledge of the authors, this study is the first one to apply ISM and MICMAC methods in the green energy adoption context. Green energy adoption is a complex phenomenon, and the implementation of these methods is of critical importance as ISM-MICMAC analysis visualises complicated problems in a simplified way (Raut et al., 2017) and provides a thorough understanding of the structural and precedence relationships among CSFs. Moreover, very few studies on green energy adoption in shipping empirically examine the opinions of stakeholders (Brauer & Khan, 2021; Mäkitie et al., 2022). The scarcity of empirical studies with practitioners is particularly evident in the green ammonia. Our study has filled this gap by analysing critical success factors through responses from a total of 48 experts from around the world.

Our study is beyond previous publications as it does not find out the most important critical success factors (Hansson et al., 2020). Our view is that each of these criteria is indispensable for the successful adoption of green ammonia. Thus, we reveal the precedence relationships between these factors to allow a roadmap required to be taken for the green ammonia adoption. Our study suggests that the main problem of alternative fuel adoption is not to find out the most important factors. Sooner or later each factor will play a major role for the adoption. For instance, comparison of cost of fuel, availability of infrastructure, and availability of propulsion technology are all essential. The cost of fuel might be found more important than infrastructure by practitioners, yet it is not quite possible to adopt alternative fuels without the necessary infrastructure of fuel distribution. Hence, we suggest that it is more relevant for the literature and policy makers to examine the relationship between them. Our results validate this view as reducing cost of green ammonia – which is found to be the most important factor in several previous papers – depends on many other antecedents and linkage factors.

5.2. Policy and practical implications

Structural relations revealed in this study illustrate the most fundamental, linkage, and dependent factors. The visualization provides policy makers and top-level industry management a clear view about actions to be taken for the successful implementation of green ammonia as a marine fuel. Our results suggest that the successful implementation compels diverse success factors including technology, infrastructure and energy investments, propulsion improvements, and maximisation of fuel availability. However, the industry and policy makers should first take actions for increasing public awareness, collaborating with stakeholders, and creating necessary financial resources.

Early practical initiatives to be taken by leading firms can be costly and require important resources. However, early adopters will also benefit in return because they trigger more public awareness, stakeholder collaboration, R&D development, and regulatory framework, which eventually will improve technological improvements, reduction in the cost, and increase in the availability of green ammonia.

One of the antecedent CSFs is carbon tax implementation which is a debated phenomenon in the green shipping domain. We acknowledge challenges of imposing carbon taxes for policy makers. However, considering carbon taxes as an incentive mechanism, our results show that financial incentives and resources are fundamental antecedents of green ammonia adoption. The importance of financial support is also validated by findings of earlier papers which indicate that the cost of green energy alternatives as a significant barrier (Brauer & Khan, 2021; Dahlgren et al., 2022).

Green ammonia adoption at large scale in the industry is neither short nor an easy journey. It requires large scale investments, R&D in renewable energy, and bunkering infrastructure. Such large initiatives compel the collaboration between government agencies and private enterprises. Hence, we suggest public-private partnerships for the successful adoption of green ammonia. The partnership between Maersk and Egypt government agencies showcases a successful example. Information sharing between maritime supply chain members for fuel management and pricing is also paramount (Surucu-Balci, Iris, & Balci, 2024). More public-private partnerships are required with the involvement of other countries and shipping companies.

The green-ammonia adoption process is likely to be heterogeneous among different shipping segments. It may be adopted faster in the liner shipping industry compared to bulk shipping as consumer products are mostly carried in liner shipping (i.e., container shipping) which can be influenced more by the public awareness and stakeholder collaboration due to Net-Zero pledges of consumer product manufacturers. Still, more examples of green energy adoption in bulk shipping started to emerge such as Atlantic Bulk Carriers opt for methanol in new ship orders. The successful adoption of ammonia necessitates mutual actions from both liner shipping and bulk shipping industries. Actions taken only by liner or bulk companies will not be sufficient. Thus, we suggest more collaboration between liner and bulk industry members.

5.3. Limitations and future research

Some limitations also exist in this study. First, our study does not focus on the organisational level of adoption factors such as leadership and management culture as the main purpose is to investigate industry-level adoption of green ammonia. Once the green ammonia fuel market becomes more mature, firm-level adoption studies can significantly contribute to understanding of ammonia adoption as a marine fuel. Our study has not differentiated fuel cells and engine fuels while examining the success factors. These two propulsion systems might differ in terms of technological maturity levels and the cost of running green ammonia. Thus, future studies targeting more refined examination may consider those differences.

No clear pathway exists today regarding which technology and energy alternative will best help to achieve Net-Zero goals of maritime supply chain. Our paper considers green ammonia as a viable option in medium and long terms and illustrates CSFs that should be accomplished to achieve commercialisation of the fuel in the industry. Though our CSFs can also be utilised for the adoption of other alternative fuels, we recommend a careful examination of factors through preliminary interviews with industry experts.

Results of this study and the roadmap drawn are based on the opinions of experts which might be subject to temporal bias. That is, expert opinions and perceptions may shift over time especially considering rapid developments in alternative fuel domain. Future studies in the similar context should be conducted to assess CSFs and relationship between them.

When conducting the ISM model, we have taken the most frequently selected relationship direction (i.e., V, A, X, O). It should be noted that not every respondent agrees on the direction of relationships in pairwise comparisons as seen in Appendix B. The opinion of experts might differ depending on their sector in the shipping industry or other demographic characteristics. Future studies can investigate differences between stakeholders in terms of CSFs, which can offer more granulated results.

The literature suggests that certain stakeholders have more influence in adoption situations (Balci & Surucu-Balci, 2021), so identification of influential stakeholders and definition of their potential contributions are key. Future studies can also scrutinise key stakeholders and their roles in green ammonia adoption.

CRediT authorship contribution statement

Gökcay Balci: Conceptualization, Investigation, Methodology, Resources, Visualization, Writing – original draft, Writing – review & editing. **Thi Tuyet Nhung Phan:** Conceptualization, Investigation, Methodology, Resources, Visualization, Writing – original draft, Writing – review & editing. **Ebru Surucu-Balci:** Conceptualization, Investigation, Methodology, Resources, Visualization, Writing – original draft, Writing – review & editing. **Çağatay Iris:** Conceptualization, Investigation, Methodology, Resources, Visualization, Writing – original draft, Writing – review & editing.

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.

Data availability

Data will be made available on request.

Appendix A. A sample of ISM questions in the survey

The following questions will ask you to indicate the relationships between 10 critical success factors. You will be asked to identify the direction of influence between two critical success factors in implementing green ammonia in the shipping industry. There are a total of four possible directions between two success factors. In pairwise comparison between Factor M and N, options are i) Factor M influences Factor N (V), ii) Factor N influences Factor M (A), iii) Both influences each other, and iv) Do not influence each other. Ten factors are indicated as below:

a) Reducing the cost of green ammonia
b) Increase of R&D in green ammonia
c) Introduction of safety regulations for ammonia as fuel
d) Development of ammonia-fuelled propulsion
e) Development of port infrastructure for green ammonia supply and delivery
f) Maximising availability of green ammonia supply
g) Support from and collaboration with stakeholders
h) Imposition of carbon taxes
i) Increase of social awareness about shipping emissions
j) Early practical actions by leading shipping companies

Comparison 1:

a) Reducing the cost of green ammonia
b) Increase of R&D in green ammonia

Answer: Select the direction of influence

o Factor a influences Factor b (V)
o Factor b influences Factor a (A)
o Both influences each other (X)
o Do not influence each other (O)

Comparison 2:

a) Reducing the cost of green ammonia
c) Introduction of safety regulations for ammonia as fuel

Answer: Select the direction of influence

o Factor a influences Factor c (V)
o Factor c influences Factor a (A)
o Both influences each other (X)
o Do not influence each other (O)

………………………
Comparison 45

i) Increase of social awareness about shipping emissions
j) Early practical actions by leading shipping companies

Answer: Select the direction of influence

o Factor i influences Factor j (V)
o Factor j influences Factor i (A)
o Both influences each other (X)
o Do not influence each other (O)

Appendix B. Frequency and percentage of relationship directions

Pairwise Comparison	Frequency and percentage of V	Frequency and percentage of A	Frequency and percentage of X	Frequency and percentage of O	Selected Direction
SF1 ➔ SF2	6	26	13	3	A
	12.5%	54.2%	27.1%	6.3%	
SF1 ➔ SF3	8	10	10	20	O
	16.7%	20.8%	20.8%	41.7%	
SF1 ➔ SF4	11	21	12	4	A
	22.9%	43.8%	25.0%	8.3%	
SF1 ➔ SF5	18	12	14	4	V
	37.5%	25.0%	29.2%	8.3%	
SF1 ➔ SF6	12	19	14	3	A
	25.0%	39.6%	29.2%	6.3%	
SF1 ➔ SF7	10	20	13	5	A
	20.8%	41.7%	27.1%	10.4%	
SF1 ➔ SF8	5	23	6	14	A
	10.4%	47.9%	12.5%	29.2%	

(continued on next page)

(*continued*)

Pairwise Comparison	Frequency and percentage of V	Frequency and percentage of A	Frequency and percentage of X	Frequency and percentage of O	Selected Direction
SF1 ➔ SF9	2 4.2%	9 18.8%	15 31.3%	22 45.8%	O
SF1 ➔ SF10	10 20.8%	10 20.8%	13 27.1%	15 31.3%	O
SF2 ➔ SF3	12 25.0%	4 8.3%	22 45.8%	10 20.8%	X
SF2 ➔ SF4	31 64.6%	3 6.3%	13 27.1%	1 2.1%	V
SF2 ➔ SF5	22 45.8%	2 4.2%	14 29.2%	10 20.8%	V
SF2 ➔ SF6	22 45.8%	3 6.3%	11 22.9%	12 25.0%	V
SF2 ➔ SF7	6 12.5%	23 47.9%	15 31.3%	4 8.3%	A
SF2 ➔ SF8	3 6.3%	24 50.0%	8 16.7%	13 27.1%	A
SF2 ➔ SF9	6 12.5%	20 41.7%	12 25.0%	10 20.8%	A
SF2 ➔ SF10	9 18.8%	22 45.8%	17 35.4%	0 0.0%	A
SF3 ➔ SF4	17 35.4%	12 25.0%	12 25.0%	7 14.6%	V
SF3 ➔ SF5	19 39.6%	10 20.8%	15 31.3%	4 8.3%	V
SF3 ➔ SF6	10 20.8%	10 20.8%	11 22.9%	17 35.4%	O
SF3 ➔ SF7	10 20.8%	21 43.8%	16 33.3%	1 2.1%	A
SF3 ➔ SF8	9 18.8%	8 16.7%	7 14.6%	24 50.0%	O
SF3 ➔ SF9	10 20.8%	19 39.6%	8 16.7%	11 22.9%	A
SF3 ➔ SF10	10 20.8%	20 41.7%	17 35.4%	1 2.1%	A
SF4 ➔ SF5	21 43.8%	8 16.7%	13 27.1%	6 12.5%	V
SF4 ➔ SF6	14 29.2%	12 25.0%	20 41.7%	2 4.2%	X
SF4 ➔ SF7	10 20.8%	20 41.7%	13 27.1%	5 10.4%	A
SF4 ➔ SF8	5 10.4%	28 58.3%	8 16.7%	7 14.6%	A
SF4 ➔ SF9	4 8.3%	18 37.5%	16 33.3%	10 20.8%	A
SF4➔ SF10	13 27.1%	18 37.5%	15 31.3%	2 4.2%	A
SF5 ➔ SF6	9 18.8%	5 10.4%	16 33.3%	18 37.5%	O
SF5 ➔ SF7	6 12.5%	20 41.7%	16 33.3%	6 12.5%	A
SF5 ➔ SF8	1 2.1%	24 50.0%	8 16.7%	15 31.3%	A
SF5 ➔ SF9	6 12.5%	10 20.8%	12 25.0%	20 41.7%	O
SF5 ➔ SF10	8 16.7%	25 52.1%	15 31.3%	0 0.0%	A
SF6 ➔ SF7	7 14.6%	21 43.8%	15 31.3%	9 18.8%	A
SF6 ➔ SF8	5 10.4%	28 58.3%	6 12.5%	9 18.8%	A
SF6 ➔ SF9	2 4.2%	13 27.1%	15 31.3%	18 37.5%	O
SF6 ➔ SF10	8 16.7%	23 47.9%	15 31.3%	2 4.2%	A
SF7 ➔ SF8	9 18.8%	10 20.8%	18 37.5%	11 22.9%	X
SF7 ➔ SF9	8 16.7%	17 35.4%	15 31.3%	8 16.7%	A
SF7 ➔ SF10	10 20.8%	7 14.6%	28 58.3%	3 6.3%	X
SF8 ➔ SF9	9 18.8%	10 20.8%	21 43.8%	8 16.7%	X
SF8 ➔ SF10	15 31.3%	18 37.5%	12 25.0%	3 6.3%	A
SF9 ➔ SF10	13 27.1%	7 14.6%	20 41.7%	5 10.4%	X

Appendix C. Information about interviewees for determining critical success factors of green ammonia adoption

Organisation	Position	Experience	Region
Container line	Customer service manager	11 years	Europe
Port terminal	Operations manager	8 years	Middle East
Clean energy consultant organisation	General manager	9 years	Asia
Governmental organisation	Renewable energy consultant	9 years	Europe
Marine and Energy Technology	General manager	15 years	Europe
University	Professor	15 years	Asia

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