

Navigating Autonomy

Factors affecting Adoption of
Autonomous Cargo Vessels and
Segments for Early Adoption

Master Thesis
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Factors affecting Adoption of Autonomous Cargo Vessels and Segments for Early Adoption

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*Vasilis Delis
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Executive Summary

The global maritime industry transports over 80% of the world's trade by volume. Yet, aging vessels, stricter environmental regulations, rising fuel costs, and growing crew shortages are forcing shipowners to rethink traditional operations. At the same time, human factors such as fatigue, skill shortages, and high labor costs contribute to inefficiencies and safety risks, driving shipowners to consider Autonomous Vessels or Maritime Autonomous Surface Ships (MASS). MASS are classified into four Degrees of Autonomy (DOA) by the International Maritime Organization, ranging from automated assistance (DOA 1) to fully autonomous operations (DOA 4).

This thesis explores the main factors that affect the adoption of autonomous vessels by shipping companies and examines how these factors vary across DOA 2 (remotely operated with crew), DOA 3 (remotely operated without crew), and DOA 4 (fully autonomous). It also identifies which vessel types and routes are most suitable for early adoption. To achieve this, a systematic literature review identified nine critical adoption factors, ranging from economic advantages and investment costs to vessel's technology reliability and maturity, regulatory clarity and emergency response capability. To quantify how shipowners prioritize these factors at different autonomy levels, the study employed the Best–Worst Method (BWM), a multi-criteria decision-making tool that gathers expert judgments. An online survey was administered to maritime professionals, each of whom provided BWM rankings for DOA 2 to 4. Consistency ratios were monitored to ensure reliable judgments. Ranking, multiple-choice, and open-ended questions captured broader expert perspectives on vessel types, routes, and overall adoption feasibility.

The results show a clear shift in priorities as autonomy increases. At DOA 2, the analysis shows that 'Investment, Development & Operational Costs' and 'Economic & Business Advantages' are the top priorities for shipowners, reflecting a cautious, financially driven approach when human oversight still mitigates technological risk. However, at DOA 3 and DOA 4, where human presence is removed, the emphasis shifts toward "Technological Maturity & Reliability" and "Regulatory & Legal Framework." This highlights that in fully autonomous environments, reliable technology and well-defined rules on liability and operations become critical. Across all autonomy levels, "Emergency Response Capability" remains a consistently high priority, reinforcing industry concerns about safety in uncrewed operations. Factors such as "Human-Capital Readiness", "Port Infrastructure Readiness", "Standardization", and "Insurance & Premiums", while necessary, rank lower at all autonomy levels.

When examining the deployment contexts, the study finds that coastal and inland routes are the most viable for early MASS implementation. These settings offer shorter distances, more stable environments, and clearer regulatory jurisdictions. DOA 2 is seen as the most practical starting point especially for trans-ocean shipping, where the need for onboard maintenance and intervention remains high. Among vessel types, containerships and Ro-Ro vessels are identified as the most suitable for early adoption due to their operational predictability and compatibility with smart port infrastructure.

This thesis advances the literature by showing that adoption drivers differ systematically across autonomy levels. This insight extends innovation adoption theory by highlighting the role of human presence in perceived risk. Unlike previous studies that evaluated autonomous shipping as a single category, this thesis emphasizes that each level of autonomy presents unique challenges and priorities. Finally, adoption will not follow a linear path but will depend on matching the right technologies with the right operational contexts. By capturing expert insights and providing level-specific analysis, this thesis offers a practical roadmap for shipowners, policymakers, and technology developers to introduce autonomous shipping.

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Introduction

Maritime transport has been in the heart of humanity, fostering exploration and connecting people. It remains the backbone of international trade, accounting for over 80% of global freight movements by volume [1]. In 2023, global maritime trade reached 12,292 million tons of goods transported [1]. At the same time, the global shipping fleet capacity grew by 3.4% in 2023, reaching approximately 2.4 billion deadweight tons (DWT)¹ [2]. However, fleet renewal rates remain below historical averages, with the global fleet age, averaging 12.5 years by DWT and over 22 years by vessel count as of early 2024. As vessels age, fuel efficiency and maintenance become more and more important concerns, driving up emissions and costs [2]. New technologies promise to make shipping smarter. But moving forward means upfront costs, new skills and updated rules. With environmental targets tightening and a volatile geopolitical landscape, shipowners must choose between falling behind or investing and adopting cutting-edge technologies to secure sustainability and future growth.

Despite the continued expansion of maritime trade, the industry faces significant challenges [1]. Relying too much on human decisions can lead to mistakes because people get tired and distracted, which can cause collisions and even environmental disasters. There is also a shortage of skilled crew and high labor costs, and long periods away from home make operations less efficient and increase the risk of seafarers being overworked [3]. Furthermore, navigating across large oceans, especially in busy shipping lanes or bad weather, often results in suboptimal routes. This inefficiency leads to higher fuel use, higher costs, and more pollution, all of which add to the industry's environmental impact.

These challenges and disruptions lead to increased operational costs, higher freight rates, and increased volatility in global supply chains [1]. In response to these pressures, industry stakeholders are increasingly turning to technological innovation as a means to overcome these challenges while improving efficiency and sustainability. As a result, shipowners and maritime stakeholders must navigate a complex landscape characterized by operational uncertainty, financial risk, and the urgent need for sustainable innovation and digitalization to improve resilience and maintain global supply chain efficiency [1].

A transformative shift in the maritime industry is the development of Autonomous Vessels or Maritime Autonomous Surface Ships (MASS) as described by the International Maritime Organization (IMO) [4]. MASS are increasingly seen as a viable solution to many of these industry challenges. They are classified according to the IMO into four Degrees of Autonomy (DOA) [4].

1. **Degree One:** Ships with automated systems that assist the onboard crew, but human operators retain full control.
2. **Degree Two:** Remotely controlled ships with onboard crew that can take over when necessary.
3. **Degree Three:** Remotely controlled ships without crew onboard, operated entirely from a remote control center.
4. **Degree Four:** Fully autonomous ships capable of making and executing decisions without human intervention.

¹Deadweight tonnage (DWT) is the maximum weight a vessel can safely carry, including cargo, fuel, fresh water, crew, provisions, and ballast. It is defined as the maximum weight minus the weight of the empty ship (hull, machinery, etc.)

These vessels have can improve operational efficiency, reduce costs, and improve safety by minimizing human error. Integrating automation and artificial intelligence lowers crew expenses, optimizes fuel consumption, and improves environmental performance [5].

However, despite the potential benefits, widespread adoption remains limited [5]. Shipowners are cautious about investing in untested technologies, particularly in an industry where reliability, safety, and compliance with international regulations are paramount [6]. The hesitation to adopt autonomous technology is further compounded by the high upfront costs and uncertainties surrounding long-term economic viability, making MASS adoption a complex decision for industry players.

Investing in MASS is therefore a complex decision-making process influenced by technological infrastructure, regulatory frameworks, organizational readiness, and economic considerations. Digitalization has increasingly become a strategic priority. However, the benefits of adopting digital technologies are not guaranteed. They depend on factors such as financial resources, organizational structure, management skills, and adaptability to new technologies. Larger and more financially stable firms are more likely to adopt advanced technologies, while smaller firms often struggle with the high costs and technical expertise required for implementation. These differences result in varying levels of efficiency and competitiveness, highlighting the need to understand the factors that influence how shipping companies evaluate autonomous investments [7, 8].

Adopting technically innovative vessels increases profitability by securing higher freight rates and reducing operational costs [6, 9]. These ships attract charterers willing to pay premiums for fuel efficiency and environmental benefits, improving financial performance. However, while these investments provide competitive advantages, they also carry risks, as the profitability of technical innovation is influenced by market conditions, fuel price volatility, and charterers' willingness to adopt newer, greener technologies. Similar considerations apply to MASS, where financial benefits depend on long-term cost savings, regulatory developments, and market acceptance of autonomous operations. Thus, for shipowners, the decision to invest in technical innovation must balance the potential for higher earnings against uncertainties in economic and regulatory environments [10].

Given the complexities involved, shipowners require structured approaches to assess the feasibility of autonomous vessel projects. Cargo transportation and specifically deep-sea, short-sea and inland shipping play the most important role in global trade. This research uses the Best-Worst Method (BWM) [11], a decision-making tool, to weigh key factors and provide new insights into what drives the adoption of autonomy. Furthermore, by applying the BWM separately for the three degrees of autonomy (DOA 2 to DOA 4), this study complements and extends previous research [12–14], by revealing how the relative importance of factors shifts across the levels of autonomy. Finally, identifying which routes and vessel types are most likely to adopt MASS can help stakeholders make informed decisions.

The focus of this Master's thesis is to bridge the gap between theoretical discussions of autonomous shipping and practical implementation challenges. It investigates the strategic feasibility of adopting the three degrees of autonomy using factors identified in the literature and insights from maritime industry experts, and key early adoption segments. Accordingly, the Research Question has been framed as follows:

What drives the adoption of autonomous cargo vessels by shipping companies, and in which segments are they likely to be introduced?

The following sub-questions will help to better understand and explore the research question:

1. What factors influence shipowners' decisions to adopt any level of autonomous maritime technologies according to existing literature?
2. Which factors are more important for shipowners from the perspectives of industry experts?
3. How do factors influencing shipowners' decisions to adopt autonomous maritime technologies differ across varying degrees of autonomy (Degree 2, 3, and 4)?
4. Which shipping segments are likely to initiate adoption?

These questions ensure a comprehensive exploration of the topic and advance academic understanding of the feasibility of autonomous vessels.

Theoretical Background

2.1. Overview of the Maritime Shipping Industry

From the age of wind-powered clippers sailing through the oceans to today's ultra-large vessels, maritime trade has continually reinvented itself to satisfy the world's ever-growing need for goods [15]. The late 1950s saw the introduction of standardized containers, sparking dramatic efficiency gains that underpinned the globalization boom of the 1980s and 1990s [15]. As a result, annual seaborne volumes climbed steadily, increasing by more than 5% between 2004 and 2008, driven largely by China's industrial rise and its demand for raw materials and manufactured products. A sharp downturn in the 2008–09 financial crisis briefly halted this expansion, but volumes rebounded into the 2010s (Figure 2.1), supported by carriers deploying larger ships and opening new long-haul trades [1, 16].

Today's market is divided among five main vessel types. Bulk carriers transport commodities in bulk and unpackaged such as iron ore, coal, grain, in ships ranging from Handymax (40,000 DWT) to Capesize (180,000 DWT), supplying routes from resource-rich exporters (Australia, Brazil) to manufacturing giants (China, Europe) [16]. Container ships have increased their capacity from 1,000 TEU¹ in the 1970s to more than 24,000 TEU today, carrying consumer and intermediate goods along the world's busiest routes: the Asia–Europe corridor via Suez and the trans-Pacific run to the U.S. West Coast [15]. Tankers, specialized for crude oil, refined products, chemicals, and LNG, span from MR (50,000 DWT) to VLCC and ULCC classes [16]. RO-RO vessels carry cars and heavy machinery between automotive hubs and foreign markets, using internal ramps to roll cargo on and off with minimal port time [17]. General cargo vessels transport a wide array of non-containerized goods such as steel, machinery, packaged foods, often on feeder and regional services that bridge smaller ports with major hubs [16].

Measuring both shipment volume and distance, ton-miles² grew faster than volume alone in the 2000s, peaking in 2009–10 as carriers rerouted to capture emerging markets [1, 16]. Although COVID-19 disruptions in 2020 drove ton-miles down even more than overall cargo volumes, the years after the pandemic have brought a strong rebound. In 2023–24, shipping volumes increased even further as ports and carriers adopted digital logistics, vessel-sharing alliances, and more flexible route networks. That pushed the average distance cargo travels from about 4,700 miles per ton in the mid-2000s to over 5,000 miles by 2024 (Figure 2.1).

Driving this growth is a complex ecosystem of carriers, ports, alliances, and regulators. Mega-hubs such as Shanghai, Singapore, and Rotterdam handle tens of millions of TEUs annually with automated cranes and deep-water berths [18, 19], while smaller ports attract traffic through digital yard management and green-energy investments [20]. Regulatory pressures, from IMO sulfur caps and carbon-intensity targets to regional Emission Control Areas (ECAs) and the EU's proposed shipping ETS, are accelerating the adoption of scrubbers, LNG bunkers, biofuels and increasingly autonomous vessel technologies [21].

¹TEU stands for Twenty-Foot Equivalent Unit, a standard measure used in container shipping. One TEU represents the dimensions of a standard 20-foot-long container (approximately 6.1 m). It is used to quantify cargo loading capacity, port throughput, and terminal handling capacity.

²Ton-miles measure the movement of one ton of cargo over one mile. They are calculated by multiplying the weight of the cargo (in tons) by the distance traveled (in miles), providing a combined measure of both volume and transport distance.

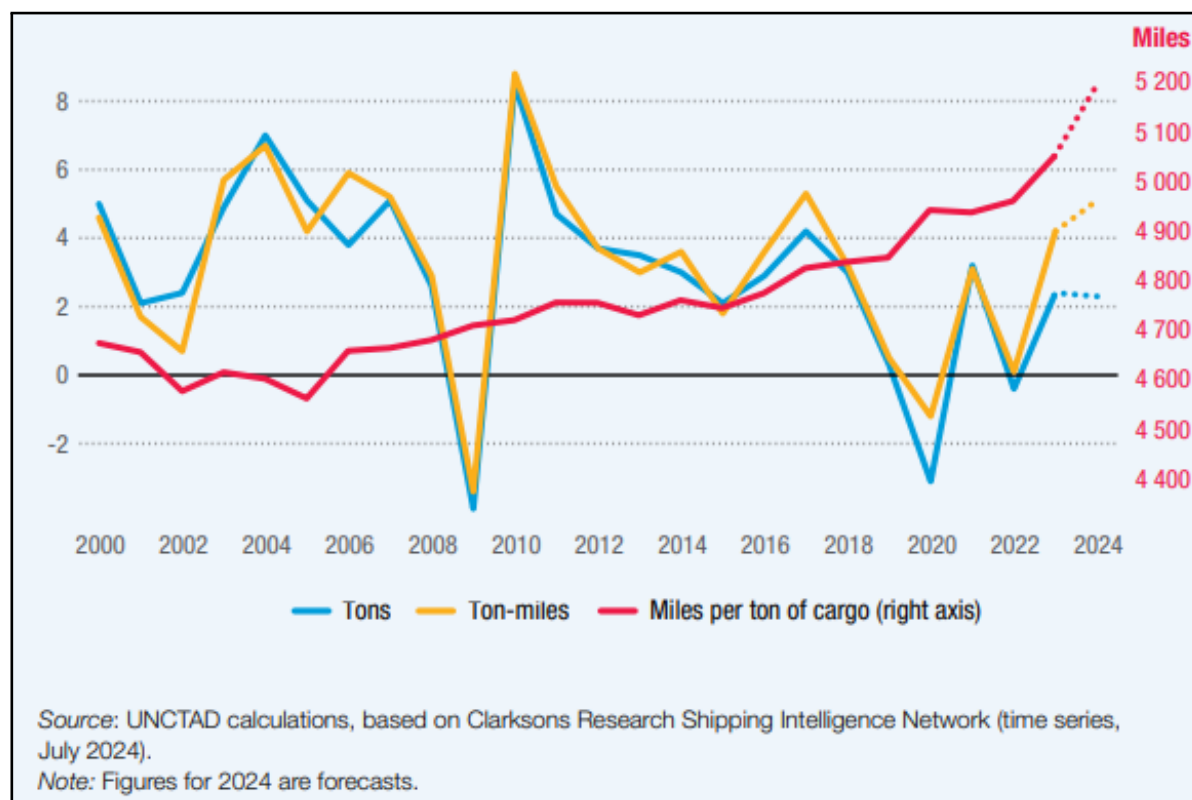


Figure 2.1: Seaborne trade growth, tons and ton-miles, and average distance travelled per ton of cargo: Trade gets a boost in 2023 and 2024 by shifting to longer shipping routes. [1]

2.2. Innovation in Maritime

The maritime industry has been through significant transformations over the centuries, driven by technological advancements and the evolving needs of trade, exploration, and warfare. Boats have been helping humanity to expand on the Earth throughout history [22]. True seagoing ships have been constructed and used for over four millennia from around 4000 BC, and maritime innovation has always been happening throughout the different periods [23], though these advances remained largely incremental until the 19th century. While new materials and designs were invented, the wind was the main propulsion force [24].

The Industrial Revolution brought a disruption in the maritime industry. A change in the propulsion systems threatened the status quo of the time. Steam engines allowed ships to travel independently of wind, greatly improving reliability and reducing voyage times. At the same time, metal hulls replaced wooden structures, improving strength and increasing cargo capacity [25].

The 20th century brought another radical innovation, the introduction of internal combustion engines [26]. These engines brought even more benefits as they are more powerful and cost-effective. However, despite their improved efficiency, they rely on fossil fuels. This has increased the interest to identify more environmentally friendly fuels and engines that can consume them [27].

Although there have been countless innovations in the maritime industry, both incremental and radical, one aspect has remained largely unchanged. This is the required crew onboard the vessels [28]. Sure, today's vessels need fewer people than they did in the past thanks to automation, but they still cannot be operated without any crew at all. That is where autonomous vessels come in. They are aiming to change the game by making it possible for ships to operate with little to no crew onboard.

2.3. What are Autonomous Vessels?

Autonomous vessels represent a major technological shift in maritime transport, integrating automation, artificial intelligence, and advanced sensor technologies to improve efficiency, safety, and sustainability [29]. The development of autonomous vessels has been driven by the need to optimize operational

costs, reduce human error, and address environmental concerns [30]. During the past decade, rapid advancements in digitalization, connectivity, and artificial intelligence have enabled significant progress in vessel automation, paving the way for fully autonomous ships.

The development of autonomous vessels has been marked by a series of milestones, including the introduction of remote-controlled and semi-autonomous ships, regulatory discussions at the IMO, and the successful deployment of fully autonomous vessels for commercial and experimental use [31]. Early forms of automation, such as autopilot systems and dynamic positioning, provided the foundations for today's remote and autonomous technologies [32]. Recent breakthroughs, such as the Yara Birkeland (the world's first fully electric and autonomous container ship) and successful trials of remotely operated commercial vessels, highlight the growing feasibility of autonomous shipping [32, 33].

Maritime Autonomous Surface Ships (MASS) are autonomous vessels designed to operate with different levels of human involvement. According to the IMO, MASS refers to ships that can navigate and perform operational functions with different degrees of autonomy, ranging from partial automation to full autonomy where no human intervention is required [34]. MASS is a key area of development in the maritime sector, with regulatory bodies, shipowners, and technology developers collaborating to integrate them safely and efficiently into global shipping. While these vessels offer numerous advantages, including reduced labour costs, increased safety, and optimized fuel consumption, challenges remain in cybersecurity, regulatory adaptation, and industry-wide acceptance. As the maritime sector moves towards digitalization, MASS is expected to play a crucial role in the future of global trade and logistics.

What does the future hold for the autonomous ships market? Roland Berger expects the market for autonomous ships to grow from about \$5.6 billion in 2023 to \$6.1 billion in 2024, then jump to \$12.2 billion by 2032, at a 9.1 % annual growth rate (Figure 2.2). Cheaper sensors, better AI navigation and remote-monitoring systems cut crew and fuel costs, while new rules from the IMO and laws like the US "SHIPS for America" Act [35] are making operators more confident in going autonomous. Successful trials, such as the Yara Birkeland [36] feeder ship, have shown that the technology works, and companies that update their yards, partner on hardware and software, or retrofit current ships will now be best placed to benefit from this fast-growing market.

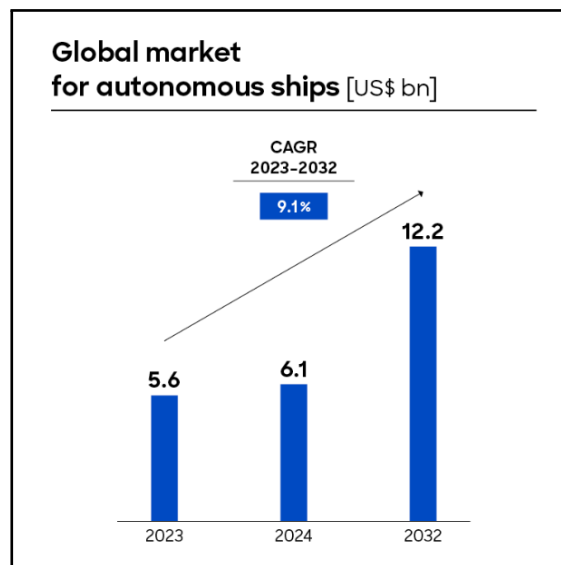


Figure 2.2: Autonomous shipbuilding set to grow three times faster than rest of sector [37].

Advantages of MASS

Autonomous ships offer significant operational cost savings due to reduced crew expenses, fuel efficiency, and optimized route planning [13, 38]. By reducing dependence on onboard crew, they also help address the global shortage of skilled maritime labor [13, 39]. Smaller crew requirements free up vessel space and can allow more flexible vessel designs [40].

They contribute to environmental sustainability through lower emissions enabled by advanced propulsion systems and more efficient navigation [38, 41]. Improved fuel management systems and predictive

maintenance technologies in MASS contribute to better lifecycle efficiency and longer vessel uptime [30]. Their deployment supports smart port integration, enabling more seamless cargo handling and reduced port turnaround times [38].

MASS improve real-time situational awareness and navigation precision through constant data streaming, AI, and sensor integration [42]. They improve safety by reducing human error, a primary cause of maritime accidents [30, 43], and enable continuous operations without fatigue-related performance drops, increasing reliability and efficiency [39]. Finally, MASS provide strategic flexibility for operators, especially in high-risk or remote areas where sending crewed ships may pose greater safety or cost concerns [44].

Disadvantages of MASS

Initial investment and development costs are high due to advanced technology requirements, new system integrations, and retrofitting needs [13, 14]. Port infrastructure around the world is not uniformly ready for autonomous vessels, leading to compatibility issues and potential delays [45, 46]. Operational reliability is a concern, especially in emergency situations where onboard crew would traditionally respond to incidents such as fires or equipment failure [30, 43].

The shortage of trained personnel and the absence of formal certification programs for remote operators hinder smooth operational transition [13, 47]. Cybersecurity threats increase as MASS are highly dependent on digital systems and communication networks [13]. There is also a lack of insurance models that are tailored to the unique risk profile of MASS, complicating liability and coverage assessments [30].

The lack of a standardized global regulatory framework complicates large-scale deployment and compliance [41, 45], while unclear international legal jurisdiction in case of accidents or malfunctions at sea adds uncertainty to MASS operations [45]. Finally, the social implications of crew displacement and job transformation create resistance among maritime unions and workers [48].

2.4. Innovation Adoption

Innovation adoption is part of the diffusion process. As described by Rogers, diffusion is the process by which an innovation is shared over time through specific channels among members of a social system [49]. This process is broken down into steps such as the development of knowledge, persuasion, decision, implementation, and confirmation. The "decision" and "implementation" steps together constitute adoption [49]. In Rogers' Diffusion of Innovations Theory, adopters are classified into five groups: innovators, early adopters, early majority, late majority, and laggards [50]. In addition, five critical factors shape the adoption process:

- Relative advantage – the extent to which a new technology is perceived as superior to existing alternatives.
- Compatibility – how well innovation aligns with current infrastructure, organizational culture, and business practices.
- Complexity – the difficulty of understanding and using the technology, with simpler innovations having a higher likelihood of adoption.
- Trialability – the ability to experiment with the innovation before full-scale implementation, which helps reduce uncertainty.
- Observability – the degree to which the benefits of an innovation are visible to others, encouraging wider adoption.

The adoption of innovation in industries, including maritime transport, is shaped by various economic, technological, and organizational factors [51]. In maritime history, a clear example of this phenomenon as already mentioned was the shift from sailing ships to steam-powered vessels, where the efficiency, speed and reliability of steam propulsion led to its widespread adoption despite initial resistance [52].

An important aspect of innovation management is technology adoption, which focuses on how individuals and organizations accept and implement new technologies. To explain and predict technology adoption and user behavior, the Technology Acceptance Model (TAM) provides information

on user behavior, highlighting that two primary factors affect the likelihood of adoption: perceived usefulness (the degree to which the technology improves efficiency or performance) and perceived ease of use (how simple the system is to operate) [53].

Over time, researchers have expanded this model to include additional elements, such as subjective norms, where adoption is influenced by social pressure or expectations from peers and industry leaders [54–56]. The three upgrades are TAM2 [54], TAM3 [56] and the Unified Theory of Acceptance and Use of Technology (UTAUT) [55]. TAM2 explains that perceived usefulness depends on more factors, such as the user's experience, voluntariness, subjective norm, and result demonstrability [54]. While TAM2 examined what affects perceived usefulness and usage intentions, Venkatesh and Bala [56] expanded this in TAM3 by also including factors influencing perceived ease of use and intention to use. As a result, TAM3 offers a comprehensive framework of all the key drivers behind IT system adoption [56]. Venkatesh, Morris, Davis, and Davis [55] combined models into the UTAUT, which identifies four key predictors of users' intention to use technology: performance expectancy, effort expectancy, social influence, and facilitating conditions [55]. This model also includes four moderators: gender, age, voluntariness and experience [55].

Beyond individual perceptions, technology adoption is also influenced by As described above, there are few firm-level perceptions of technology adoption models.

The Technology–Organization–Environment (TOE) framework highlights three contextual factors, technology, organization, and environment, that shape how firms adopt and implement new technologies [57]. The technological context includes the firm's existing practices and equipment, as well as the technologies available outside the firm [57]. The organizational context covers characteristics like the firm's size, scope, and management structure [57]. The environmental context describes the firm's operating landscape, including its industry, competitors, and government involvement [57].

Specifically, to assess the innovation and potential adoption of MASS, Fonseca et al. [40] developed the Technology Adoption (TechAdo) model. This model evaluates technology adoption across three key pillars: technical feasibility, human capital, and economic benefits, while also considering the enabling environment (e.g., regulation, governance, and social acceptance) [40]. This comprehensive method highlights that while MASS is technically feasible, its adoption is still in the early stages, and broader socio-economic and regulatory factors have been underexplored and need greater attention [40].

From a strategic perspective, companies influence the adoption of new technologies by making calculated market entry decisions and employing competitive strategies [58]. Research has highlighted that factors such as early adoption timing and pricing mechanisms, including penetration pricing (where firms temporarily set prices below costs to encourage adoption), significantly impact whether a new technology gains dominance [59]. Companies play an essential role in shaping market preferences, as their investment decisions and technology choices determine which solutions gain widespread acceptance [60]. When considering these factors in the maritime industry, various challenges impact the adoption of new technologies [48]. Although digital innovations such as real-time fleet monitoring, fuel optimization systems, and predictive maintenance tools have been shown to improve operational efficiency, they are not adopted uniformly across the sector [7].

2.5. Barriers to innovation adoption in maritime industry

Compared to other sectors and even transportation modes, the maritime industry has traditionally taken a more cautious approach to innovation. This is largely because many shipping companies prefer to stick with familiar ways of working, are careful about taking financial risks, and often wait to see how new technologies perform in other industries before deciding to adopt them [61]. Barriers that hinder innovation adoption are multiple and come in all sizes and shapes.

2.5.1. Technological Challenges

Developing reliable autonomy for large ships has proven more difficult than forecasts early assumed [62]. Robust AI navigation and sensor fusion systems are required to detect and avoid collisions in open oceans and congested waterways. Current prototypes still struggle with real-world complexities such as poor visibility, heavy traffic, or unexpected obstacles [62]. High-precision sensors (radar, LIDAR, cameras, sonar) and redundant control systems must perform flawlessly for extended periods at sea.

Ensuring continuous connectivity through satellite is another challenge. Autonomous vessels need reliable communication links for remote monitoring or control, yet satellite coverage can be spotty or latency-prone in certain regions [63, 64]. Cybersecurity is also an important concern. An autonomous vessel's guidance systems could be vulnerable to hacking or signal interference, posing safety and liability risks if not fully secured [13]. Furthermore, collision avoidance is particularly critical. Industry experts rank advanced anti-collision systems as the top requirement for commercial autonomy [13]. Introducing autonomous vessels in ports involves several technological challenges, such as ensuring stable surface communication, reliable real-time data exchange, and smooth integration with existing port systems and infrastructure [65]. In short, the technology is advancing, but not yet at a level where shipowners trust it with million-dollar vessels and cargo.

2.5.2. Economic and Financial Barriers

The initial investment for autonomy is very high [6]. Outfitting a cargo ship with autonomous technology (sensors, control systems, redundant propulsion and power, and communication equipment) can add significant cost [6]. Studies indicate that converting an existing conventional ship to autonomous operation could increase the capital cost by around 8–17% [38]. Designing a new ship without crew facilities can save some money (eliminating the crew accommodations and bridge might cut 5% of construction cost), but the need for sophisticated automation equipment adds roughly another 10% to the build cost [6]. The net effect is that a new autonomous-ready vessel might still cost slightly more (3–14% higher CAPEX) than a traditional ship, according to an analysis [38]. For example, Yara Birkeland, cost about \$25 million to build, almost triple that of a comparable conventional vessel. This premium was in part due to its electric propulsion and automation. In return, Yara Birkeland aimed to save up to 90% of operating costs by cutting out fuel and crew [66]. However, such a high initial cost makes many shipowners and financiers reluctant to commit, especially in a competitive industry with tight margins. Uncertainty about return on investment (ROI) is a major barrier [6]. If technology or regulations evolve, today's expensive autonomous system could become obsolete or non-compliant, risking the investment [45].

2.5.3. Safety Concerns

Safety remains a challenge for the adoption of autonomous vessels [67]. The maritime community is particularly cautious about removing seafarers, who play a critical role in responding to emergencies, system failures, and unexpected situations at sea [29]. Regulators and insurers require proof that autonomous systems can meet or exceed the safety standards of human-operated ships before granting widespread approval [68]. In addition, safety concerns extend to practical operational challenges, such as search and rescue obligations (an unmanned vessel may be unable to help other ships in distress and emergency handling, including fire suppression and machinery failures that traditionally rely on a crew onboard) [69, 70]. These uncertainties contribute to a "wait-and-see" approach in the industry, where many stakeholders hesitate to commit to full-scale adoption until safety issues are adequately addressed [71].

2.5.4. Regulatory Challenges

The regulatory landscape presents significant obstacles to the deployment of autonomous vessels [45]. Current international maritime regulations, such as the International Regulations for Preventing Collisions at Sea 1972, also known as Collision Regulations (COLREG) and the Safety of Life at Sea Convention (SOLAS), were drafted with the assumption that human operators would always be present for navigation and watch-keeping duties [68]. In some countries, national laws create additional barriers. For instance, US regulations require a minimum crew on certain ships and rarely allow exceptions. [72]. As a result, even if a ship is technically capable of operating without seafarers, legal constraints can still require human personnel on board, undermining the economic viability of autonomous shipping [73]. To address these challenges, the IMO is developing a regulatory framework for MASS. [72]. This framework is expected to be finalized in 2025 and could enter into force by 2032 [72]. However, until international conventions are updated to clearly define liability, insurance responsibilities, and operational rules for autonomous ships, many shipowners remain hesitant to invest in these technologies.

2.5.5. Operational and Integration Challenges

Even if the technology works, integrating autonomous vessels into today's maritime operations is complex [74]. Ports and terminals are traditionally designed for manned ships. Port pilots board vessels to guide them in, crews handle mooring lines, and regulators insist on human oversight in congested harbours [75]. Adopting autonomous cargo vessels means that ports need new protocols (or automation on the port side) for docking and unloading without crew [76]. This integration concern is significant: shipowners worry about the "last mile" problem. A vessel could sail autonomously offshore but still require manual intervention in port approaches or canals [77]. Industry stakeholders also point out that autonomous ships would need maintenance support in ports [78]. Without engineers on board, more repair and maintenance tasks shift to shore-based teams when the ship docks. This requires scheduling and potentially longer port stays or highly efficient turnaround processes [79]. Additionally, mixed traffic situations (autonomous vessels sharing waters with crewed ships, fishing boats, recreational craft, etc.) create operational uncertainty. Autonomous systems must reliably interpret and predict the behaviour of others, which is challenging [71]. There is also resistance from labor organizations concerned about crew integration: maritime unions have raised alarms that replacing experienced crews with AI or one remote operator overseeing multiple ships could compromise safety and job security [62]. In general, the conservatism of the maritime sector, born of safety-first culture and decades-old practices, means new systems must integrate gradually and prove themselves. Until autonomous vessels can seamlessly fit into the logistics chain (from port operations to insurers and customers), adoption will remain slow [30].

2.6. Factors affecting innovation adoption by shipowners

Adopting cutting-edge maritime technology is both an investment opportunity and a financial risk [80]. Shipowners must carefully perform cost-benefit analyses and risk assessments before committing to innovations such as autonomous systems, new fuels, or digital platforms [6]. In addition, the reliability of new technologies and the clarity of regulatory frameworks may play an important role in shaping adoption decisions [6]. The factors chosen below are linked to the TAM and Rogers' Diffusion of Innovation theories. These theories help explain why shipowners might care more about some benefits of autonomy and which factors can speed up or slow down adoption at each autonomy level [81]. This section reviews the existing literature on the selected factors that will be analyzed in more detail later.

2.6.1. Economic and Business Advantages

MASS present numerous potential economic advantages that could revolutionize the shipping industry [13]. A key benefit lies in the significant reduction of crew-related expenses which typically constitute 5-15% of a vessel's operating costs. These savings emerge from lower requirements for salaries, training, insurance and onboard accommodations [42]. Minimizing or removing crew facilities also enables increased cargo capacity and improved ship design efficiency, increasing profitability and lower fuel consumption due to reduced vessel weight [9]. Kretschmann et al. found that the expected present value of costs over 25 years for an autonomous bulk carrier was \$4.3 million lower than that of a conventional vessel, allowing it to operate with a 3.4% lower freight rate [9].

Autonomous vessels also benefit from operational optimizations enabled by real-time data processing, which reduces delays and optimizes energy use [30]. Business models like the mother-daughter vessel scheme or logistics-on-demand can lower costs by 11-20% through better asset utilization [82]. The AUTOSHIP project further confirms this potential, estimating a 52.3% Financial Rate of Return (FRR) based on reduced operation and maintenance costs combined with increased cargo throughput [41].

From an environmental perspective, MASS can significantly reduce emissions. For instance, Dantas et al. showed that autonomous short-sea vessels could cut CO₂ emissions by 28-33% and NO_x by 26-31%, due to more efficient operations and reduced onboard energy needs [38]. Additionally, AI-powered systems allow for dynamic route and speed optimization, which enhances both fuel efficiency and emissions performance [30]. These environmental advantages not only improve compliance with international maritime regulations but also contribute to a stronger business case by lowering fuel and environmental compliance costs [83].

2.6.2. Investment, Development and Operational Costs

Investment and development costs are always very important for new innovations and might slow down the adoption MASS [13]. Building a new autonomous ship can cost up to three times more than building a conventional vessel. due to the integration of advanced sensor technologies, redundant systems, and complex ICT platforms required for autonomy [13, 30]. In contrast, retrofitting existing vessels may lower initial capital expenditures, but often introduces design limitations and increased long-term maintenance demands due to hybrid system complexity [9, 44]. The MUNIN project estimated that while autonomous ships remove accommodation and crew-related costs, they incur an additional 10% capital cost due to the integration of autonomous navigation and remote-control systems [9].

Up-front R&D costs are also substantial, especially during the prototyping and testing phases, which require specialized AI algorithms, maritime sensor arrays, and cybersecurity infrastructure [6]. Training costs are another critical aspect. While autonomous ships reduce the number of onboard crew, they require a new class of remote control centers operators trained in systems integration, remote diagnostics, and automated navigation management [30, 42]. Developing and implementing these specialized training programs adds to long-term operational costs [30].

Furthermore, ongoing operational expenses such as remote operation centers staffing, maintenance of autonomous systems, and continuous connectivity, can partially offset savings from reduced onboard crew [13, 42]. Maintenance is further complicated by the limited availability of specialized dry docks and the requirement for manufacturer intervention in the event of system failure or software updates [40].

2.6.3. Insurance and Premiums

Insurance and premiums are central concerns in the adoption of MASS, as current frameworks are largely designed for conventionally manned vessels [6, 41]. The absence of long-term operational data and standardized risk models has made insurers cautious in underwriting policies for autonomous ships, often resulting in higher premiums or limited coverage [6]. The risk profiles of MASS are still evolving, especially in relation to cyber vulnerabilities, human-automation interaction, and real-time decision-making under uncertainty [42]. Furthermore, uncertainty about who is responsible for incidents involving autonomous systems, such as operators, software providers, or owners, has complicated claims processing and delayed insurer adoption of MASS-specific policies [83].

Recent legislative developments, such as the UK's draft Vehicle Technology and Aviation Bill, propose that insurers be held liable for damage caused by insured autonomous vehicles, including potentially MASS, shifting some liability burden away from operators and toward insurers [39]. This framework is supported by risk-sharing provisions that allow insurers to seek compensation from third parties (e.g., software developers), representing an early model of a tailored MASS liability system. Currently, traditional marine insurances such as Hull and Machinery (H&M) and Protection & Indemnity (P&I) remain applicable in concept, but many underwriters are hesitant to apply them without modifications for autonomous contexts. Insurance schemes could evolve into dynamic hybrid models in which liability is shared among shipowners, ROC operators, and technology providers, based on factors such as the degree of autonomy, route complexity, and real-time monitoring data. Until such frameworks are widely adopted and standardized internationally, the lack of clear insurance options remains a significant barrier to large-scale deployment of autonomous ships [82].

2.6.4. Vessel's Technological Maturity and Reliability

Maturity and reliability of technology are key determinants for the adoption of MASS, as they influence both safety assurances and commercial feasibility [13]. Despite ongoing progress, many MASS technologies, particularly in navigation, control systems, and situational awareness, are still undergoing prototyping and field testing [40].

Sensor and communication systems are critical for the autonomous vessel's ability to perceive and respond to maritime environments. However, they are still prone to calibration errors, latency, and connectivity issues that can affect decision-making and increase operational risk [83]. Common failures include malfunctions in propulsion systems, collision-avoidance modules, and AI software used for decision-making, highlighting the importance of building redundancies and rigorous testing protocols [30]. In studies of MASS configurations, reliability was rated the top factor influencing commercial

viability, especially concerning anti-collision and anti-grounding navigation systems, which are essential in mixed traffic environments [13].

Whilst not only onboard vessels, human-machine interfaces onshore and onboard are crucial aspects included in the vessel's technological development [14]. Easy to use human-machine interfaces (HMI) help shore-based operators read data, track ship movements, and make quick and accurate decisions. Poorly designed interfaces can cause confusion and errors, especially in high-pressure situations [84]. Staying aware of what is happening at sea is harder from shore, since operators depend on screens, sensors, and software to understand the ship's surroundings. To improve this, ROCs use live video, radar overlays, and 3D visuals to help operators see what the ship sees [85]. Smart decision-support tools, such as AI-based alerts and scenario simulations, help reduce mental stress and guide operators during tricky events such as route conflicts or technical issues [86].

As MASS depend on interconnected digital systems, cybersecurity is one of the most critical challenges for their safe and reliable operation [13, 87]. Because these vessels depend on communication networks, artificial intelligence, and remote control systems, there are more exposed to cyber threats than traditional ships [88]. Key navigation and control components and the Remote Operation Centres are particularly exposed to risks such as signal spoofing, system manipulation, and hacking [13]. Many autonomous ship designs still fail to consider cybersecurity from the ground up, leaving critical systems such as AIS, GNSS, sensors, and cameras susceptible to exploitation [88].

Without seafarers onboard, autonomous vessels face new security challenges, including increased risks of piracy and hijacking.[30, 89]. The lack of crew makes it easier for pirates to physically board, seize control, or tamper with equipment and cargo without immediate resistance [30]. Security risks for MASS also include theft, sabotage, smuggling, and even the use of ships as tools for terrorist activity, all of which are exacerbated by reduced onboard surveillance and protection systems [90]. In high-risk areas, the traditional use of armed security or defensive measures such as barbed wire, water cannons, and secure compartments must be adapted or automated for unmanned ships [30]. While physical countermeasures can offer some defense, AI-based surveillance and alert systems are still under development and are not yet reliable substitutes for trained security personnel [91].

2.6.5. Port Infrastructure Readiness

On the other side of the vessel's technology there is the port infrastructure [91]. MASS operations are heavily dependent on high-speed data exchange, remote monitoring, and automated handling, all of which require substantial upgrades to both the digital and physical port infrastructure [30]. As autonomous ships rely more on real-time data for communication and navigation, ports need strong digital infrastructure, including reliable internet, integrated sensors, and big data systems, to manage continuous information flow. [45, 91]. Effective port-side security is essential for safe operations involving autonomous and connected vessels. Ports must implement a range of cybersecurity measures, including secure data links, access controls, and anti-tamper systems, to protect critical infrastructure and ensure data integrity during ship-to-port interactions [92].

Smart ports must also incorporate automated mooring, automated cargo handling systems, and remote document verification through e-government platforms, aligning port services with MASS requirements [43, 45]. Reliable MASS operations require updated surveying and mapping tools, navigation data repositories, and infrastructure capable of processing inputs in real time to support safe docking and undocking operations [45]. Ports that are unprepared for such changes face the risk of being excluded from future autonomous shipping corridors, particularly as smart port development accelerates in nations that invest in innovation [91]. Therefore, coordinated efforts are needed from port authorities, infrastructure developers and public agencies to ensure infrastructure compatibility, real-time data handling, and automation support in critical maritime hubs [30, 45].

2.6.6. Standardization

The lack of international standards remains one of the most significant obstacles to the widespread adoption of MASS. Without standard protocols, stakeholders face uncertainty in system design, operational expectations, and compliance requirements across jurisdictions [30, 93, 94]. Because the systems are not standardized, autonomous ships and ports cannot easily work together, making it a challenge to expand these operations worldwide. Developers and shipowners have called for unified

frameworks that cover data exchange, communication systems, and performance benchmarks to facilitate consistent deployment and certification of MASS technologies [91].

Technical standards are also essential to ensure safety and reliability in remote and autonomous operations. Currently, variations in autonomy levels, software architectures, and sensor configurations make it difficult to establish universally accepted testing and validation criteria, which hinders confidence among insurers, regulators, and end-users [45]. For example, the absence of standardized protocols for human-machine interfaces and decision-making algorithms complicates liability assignment and complicates risk management strategies in mixed-traffic scenarios [30, 93, 94].

2.6.7. Emergency response capability

As vessels move toward full autonomy and operate without seafarers, reliable emergency response capabilities become a critical safety requirement for MASS [14, 90]. Without onboard personnel, these ships must depend entirely on remote operation centers, autonomous decision-making, and embedded safety systems to detect and respond to incidents such as fire, flooding, and propulsion failure [30]. Existing MASS systems are not yet equipped with autonomous emergency protocols capable of handling complex failures without external input [30, 43]. The Hybrid Collision Avoidance (COLAV) model integrates high-level planning, predictive control, and emergency maneuvering compliant with COLREG, offering short-term collision mitigation but not long-duration failure management [95]. Models show that solutions, such as remote override, automated scheduling, and sensor-equipped buoys, can reduce risk in environments like ports, but full emergency protocols for deep-sea autonomous ships are not yet in place [91]. Until MASS can autonomously manage multi-failure events their deployment in open-ocean commercial operations will remain limited [30, 47].

2.6.8. Human-Capital Readiness

Except for MASS levels that still require minimal crew onboard for maintenance and emergency response, the roles involved in higher levels of MASS operations differ from traditional seafaring. They demand skills in system diagnostics, cyber-physical systems, remote operations, and data analysis. [47]. This shift creates a growing need for personnel cross-trained in maritime operations and digital systems, combining expertise in navigation, engineering, information technology, and cybersecurity [96].

However, structured training programs and certifications tailored to MASS remain limited. There is currently no standardized qualification framework recognized globally for remote ship operators or remote control center (RCC) personnel [97]. As a result, education providers and maritime institutions are beginning to explore hybrid curricula that combine simulator training, AI interaction, and scenario-based decision making [47]. Munim et al. emphasize that more research is needed on the human-readiness capabilities factor and its importance compared to others, as required skills and competencies are not yet clearly defined [13].

2.6.9. Regulatory and legal framework

The regulatory and legal framework for MASS is under development as current frameworks are not designed for autonomous operations [39, 91]. IMO is working to update current maritime regulations to match different levels of ship autonomy [4]. In 2021, the IMO finished a study called the Regulatory Scoping Exercise (RSE), which looked at how current laws apply to autonomous ships and what needs to change [88]. This led to the creation of a special working group, the Joint MSC-LEG-FAL Working Group on MASS, to handle key issues such as safety, legal duties, and ship-port procedures [98]. One of the group's major outcomes is the draft of a new MASS Code, which is expected to be adopted as a guideline in 2026, and later as a mandatory code in 2028 [4]. Current laws like SOLAS and COLREG assume that people are on board, so they need to be updated to work with autonomous systems [99]. The IMO is working to ensure that the legal system keeps up with new technology, so autonomous ships can be operated safely and legally around the world [4].

The situation is even more challenging for inland shipping in Europe, where many different authorities enforce the rules [45]. A major legal issue is how to define key roles, such as the captain, when there are no seafarers on board. There is also no agreement yet on how much autonomy should be allowed [39].

2.7. Segments for MASS Adoption

The most widely supported scenario for early MASS adoption involves small-sized feeder container vessels operating on short-sea shipping routes in regions like the Mediterranean and Baltic Seas. These routes are preferred due to short distances, frequent voyages, well-established port infrastructure and networks, and predictable weather and navigation conditions [13]. Projects such as MUNIN and ReVolt demonstrated the potential of autonomous technologies in inland waterways and coastal routes [6].

While other kinds of vessels such as regional passenger ferries and offshore wind farm vessels might be well suited for early adoption, containerships and Ro-Ro vessels lead the way in cargo transport [100].

Finally, although trans-ocean vessels might benefit from automation, they face considerable hurdles such as cybersecurity and maintenance demands and communication challenges in open oceans [6].

2.8. Multi-Criteria Decision-Making in Maritime Adoption

To better understand the importance of the different factors for the different degrees of autonomy, we use a Multi-Criteria Decision-Making (MCDM) framework. MCDM is a systematic approach used by decision-makers to evaluate complex decisions involving multiple conflicting criteria. In the maritime sector, adoption decisions often require balancing technological feasibility, financial considerations, regulatory compliance, and operational constraints [12–14, 101]. MCDM techniques help simplify complex decisions by organizing different factors and opinions of stakeholders, leading to choices that are well informed, clear, and easy to explain. Three popular MCDM approaches are the Analytic Hierarchy Process (AHP) [102, 103], the Analytic Network Process (ANP) [104] and the Best–Worst Method (BWM) [11]. In this study we implemented the Best–Worst Method to understand the importance of the different factors.

2.8.1. Best–Worst Method (BWM)

BWM streamlines expert input by asking each expert to pick the single most important factor (“best”) and single least important factor (“worst”) [11]. The expert then compares the best criterion against all others, and all others against the worst, needing fewer than AHP or ANP [11]. BWM also includes a consistency check to ensure that the results are reliable [11]. However, since BWM depends on each expert’s selection of the best and worst criteria, any bias or misunderstanding at that stage affects the final weightings. Additionally, because BWM is based on individual judgments, combining inputs from multiple experts often involves averaging, which can reintroduce inconsistencies.

While BWM was introduced only 10 years ago, it has been applied to many research projects. In the agricultural sector, Li et al. used it to understand the preferences of Japanese rice farmers for adopting an organic agriculture system and innovative machinery [105]. Alijani et al. researched the prioritization of different paddy cultivation areas in Iran based on sustainability criteria [106]. In the logistics sector, it has been used to understand the environmental, social and economic aspects of sustainable freight transportation in Africa [107]. To evaluate the service quality of old-chain logistics in air freight a perception-expectation gap model based on the fuzzy BWM [108]. Ding et al. performed an assessment of key risk factors in the cold chain logistics operations of container carriers [109]. The method has also been implemented in the transportation sector [110–113].

2.8.2. Application of Best–Worst Method in Autonomous Vessel Projects

Multi-Criteria Decision-Making (MCDM) methods are particularly well suited to evaluate autonomous vessels due to the complexity and variety of factors involved such as technological, economic, regulatory, and operational. These methods allow decision-makers to systematically assess and weight these diverse criteria based on their relative importance, enabling more strategic and informed investment decisions by shipowners and maritime stakeholders [11].

The Best–Worst Method (BWM) was selected for this study because it offers multiple advantages over other more traditional techniques (AHP, ANP) [12, 114]. Developed by Rezaei in 2015, BWM reduces the cognitive load on experts by requiring only $2n - 3$ for n criteria [11], as opposed to AHP’s $n(n - 1)/2$ pairwise comparisons [103]. This simpler process makes it easier to use while still giving accurate results.

BWM also improves consistency by directly linking the most and least important criteria with all others, rather than requiring equal pairwise comparisons among all criteria [11]. This structured approach has been shown to produce more reliable outcomes, as evidenced by comparative studies that found that BWM yielded greater internal consistency than AHP [115].

Recent applications of the Best–Worst Method (BWM) in maritime autonomy have highlighted different priorities depending on the sailing scenario [12, 13]. In a Bayesian BWM study, nine commercialization criteria were assessed across varying autonomy levels and shipping routes. Navigation systems (anti-collision/anti-grounding), cybersecurity risks, and capital costs received the highest weights, with short-range, degree 2 autonomous feeder vessels on intra-European routes identified as the most viable option [13]. In another study focused on Arctic shipping, classical BWM was used to evaluate four options against eight criteria. The experts prioritized operating costs, navigation in harsh conditions, and environmental protection. The study concluded that while conventional manned ships remain the most practical today, shore-controlled semi-autonomous vessels and platooning hold the most promise in the near term [12].

In summary, using the Best–Worst Method offers a clear and efficient way to identify the most and least important factors, while also assessing the relative importance of all others, across different degrees of autonomy. This approach helps determine whether these priorities change with varying autonomy levels, enabling shipping companies to make well-informed decisions based on a consistent understanding of the key factors influencing innovation adoption.

3

Methodology

3.1. Research Design

To address the research question, a comprehensive methodology was developed consisting of the following phases:

- Identification of factors through systematic literature review and expert input.
- Quantitative prioritization of factors for the different degrees of autonomy using the Best-Worst Method (BWM).
- Comparison of factors between different degrees of autonomy.
- Analysis of the survey's ranking questions on vessel types and sailing routes implementing the Borda's Method to identify preferred options.
- Open-ended questions that provide qualitative information on MASS adoption, supported by direct quotes from participants.

3.2. Literature Review and Expert Input

A structured method was used to identify factors that influence shipowners' decision to adopt MASS. The literature search was performed using the Scopus database, where the following Boolean expression was used: ("autonomous ship" OR "autonomous vessel" OR "maritime autonomous surface ship" OR "unmanned vessel") AND ("innovation adoption" OR "technology adoption" OR "adoption"). This expression returned a total of 513 records. To focus on the most relevant studies, the search was filtered by titles, abstracts, and keywords of the articles. This search returned 58 records. The search was conducted in March 2025. After screening the abstract, introduction and conclusion of these articles, for relevance to factors that affect the adoption of autonomous vessels, 8 articles [6, 13, 14, 30, 40, 45, 81, 82] were retained as relevant.

The analysis of these articles identified 63 factors. Factors were included in an Excel file when they were explicitly or implicitly mentioned. Implicitly mentioned factors were identified through thematic reading of the text for mentions of challenges, enablers, or concerns that influence technology adoption, even when they were not explicitly labelled as factors.

To prevent the pairwise comparison from growing extensively as we wanted to perform the BWM for different DOA, the factors were narrowed to a list of 9 based on importance and input of two experts in the maritime industry and two researchers on autonomous vessel technologies. The criteria used to narrow down the results included relevance, frequency of mention in the literature, practical importance, and feasibility of comparison within the BWM framework. An extensive review of these selected factors is presented in the previous chapter. In chapter 4, we present the a description of the detailed components.

3.3. Best-Worst Method on Different DOA

Following the identification and classification of factors, the Best-Worst Method (BWM) is applied to prioritize the importance of each factor. The method begins by identifying the most and least important factors. Experts then provide two key sets of comparisons: first, by evaluating how much more important the best factor is compared to each of the other factors (constructing the best-to-others vector), and second, by assessing how much each factor is preferred over the worst criterion (resulting in the others-to-worst vector).

These preference vectors are then utilized within a framework to derive the optimal weights for each factor. This approach increases consistency and reduces subjectivity, making the decision-making process simpler and more reliable. Therefore, the application of BWM supports more informed and strategic decision-making in complex scenarios.

Out of the four degrees of autonomy (DOA), three are assessed:

- Degree Two (D2): Partially crewed vessels designed for remote operation from a Remote Operation Centre (ROC).
- Degree Three (D3): Remotely operated vessels with no crew onboard.
- Degree Four (D4): Fully autonomous vessels capable of independent decision-making without human intervention.

3.4. Steps of the Best-Worst Method

3.4.1. Select the Best and Worst Criteria

From the list of the key factors that were identified previously, the decision-makers chooses the most important criterion (best) and the least important one (worst). The respondents were asked "Which factor do you consider the Most important overall?" to identify the most important factors of autonomy and "Which factor do you consider the Least important overall?" to identify the least important factors.

3.4.2. Rate Best-to-Others

After identifying the most important criterion, the responders were asked "Indicate how much more important is the "most important factor" over each of the remaining 8 criteria". In this way, they rate how strongly the best criterion is preferred over each of the other criteria using a scale from 1 (equal importance) to 9 (absolutely more important). This creates the Best-to-Others (BO) vector. The resulting Best-to-Others vector would be [11]:

$$A_B = (a_{B1}, a_{B2}, \dots, a_{Bn}) \quad (3.1)$$

where a_{Bj} indicates the preference of the best criterion B over criterion j. It is clear that $a_{BB} = 1$.

3.4.3. Rate Other-to-Worst

Then the responders were asked "Indicate how much more important are the remaining criteria compared to the "least important factor". This way they rate how each criterion is preferred over the least important using the same scale from 1 (equal importance) to 9 (absolutely more important), excluding the most important factor to minimize inconsistencies as this was ranked in the previous question. This creates the Best-to-Others (OW) vector. Others-to-Worst vector would be [11]:

$$A_W = (a_{1W}, a_{2W}, \dots, a_{nW})^T \quad (3.2)$$

where a_{jW} indicates the preference of the criterion j over the worst criterion W. It is clear that $a_{WW} = 1$ [11].

3.4.4. Compute Optimal Weights

After we collect the Best-to-Others scores a_{Bj} and the Others-to-Worst scores a_{jW} , we want to find weights $w_1, w_2, \dots, w_n$ that match those scores as well as possible. The following problem is resulted, considering the non-negativity and sum condition for the weight [11].

$$\min_{w_1, \dots, w_n} \max_{j=1, \dots, n} \left\{ \left| \frac{w_B}{w_j} - a_{Bj} \right|, \left| \frac{w_j}{w_W} - a_{jW} \right| \right\} \quad \text{subject to} \quad \sum_{j=1}^n w_j = 1, \quad w_j \geq 0.$$

To solve this with standard linear-programming tools, introduce a new variable ξ that stands for that “maximum mismatch.” Then we solve

$$\min_{w_1, \dots, w_n, \xi} \xi$$

subject to these rules for each $j = 1, \dots, n$:

1. The ratio of the best weight to w_j should be close to a_{Bj} :

$$\left| \frac{w_B}{w_j} - a_{Bj} \right| \leq \xi.$$

2. The ratio of w_j to the worst weight should be close to a_{jW} :

$$\left| \frac{w_j}{w_W} - a_{jW} \right| \leq \xi.$$

3. All weights add up to 1:

$$\sum_{j=1}^n w_j = 1.$$

4. No weight is negative:

$$w_j \geq 0 \quad \text{for all } j.$$

Putting it all together:

Minimize ξ ,

so that for each j :

$$\begin{aligned} \left| \frac{w_B}{w_j} - a_{Bj} \right| &\leq \xi, \\ \left| \frac{w_j}{w_W} - a_{jW} \right| &\leq \xi, \\ \sum_{j=1}^n w_j &= 1, \\ w_j &\geq 0. \end{aligned} \tag{3.3}$$

Consistency Ratio

Once the optimal weights $w_1, \dots, w_n$ (including w_B and w_W) have been obtained, we evaluate how consistent the expert's pairwise judgments are via the *Consistency Ratio* (CR) as in Liang et al. [116]. First, define for each criterion j the individual consistency index

$$CR_j = \begin{cases} \frac{|a_{Bj} a_{jW} - a_{BW}|}{a_{BW} a_{BW} - a_{BW}}, & a_{BW} > 1, \\ 0, & a_{BW} = 1, \end{cases}$$

Then the overall consistency ratio is

$$CR = \max_{j=1, \dots, n} \{CR_j\}.$$

We compare this CR to the threshold value corresponding to our number of criteria n and the 1–9 scale. If CR exceeds that threshold, the pairwise inputs a_{Bj} , a_{jW} must be revised until CR falls below (or equal to) the permitted limit [116].

Number of Criteria (m)	Comparison Scale Size						
	3	4	5	6	7	8	9
3	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667
4	0.1121	0.1529	0.1989	0.2206	0.2527	0.2577	0.2683
5	0.1354	0.1994	0.2306	0.2546	0.2716	0.2844	0.2960
6	0.1330	0.1990	0.2643	0.3044	0.3144	0.3221	0.3262
7	0.1294	0.2457	0.2819	0.3029	0.3144	0.3251	0.3403
8	0.1309	0.2521	0.2958	0.3154	0.3408	0.3620	0.3657
9	0.1359	0.2681	0.3062	0.3337	0.3517	0.3620	0.3662

Table 3.1: Thresholds for Acceptable Consistency Ratio (adapted from Liang et al. [116])

In our implementation, the same Excel-based BWM solver that produced $\{w_j\}$ also returns the value of CR. We then verify that

$$CR \leq (\text{threshold from Table 3.1 for } m = 9),$$

If CR exceeds this threshold, the decision-maker must revise the pairwise judgments until consistency is acceptable. Because such revisions cannot be performed through the survey alone, any response with $CR > 0.3662$ was excluded from our analysis. From our survey, one pairwise comparison on DOA 4 exceeded the threshold and was removed from the final results.

By solving this problem using BMW Excel Solver (<https://bestworstmethod.com/software/>), we result to the best possible weights w_j and the smallest ξ , which identify the largest error that should be avoided.

3.5. Calculation of Global Weights

3.5.1. Aggregation

The optimal weights derived from individual responses are normalized and averaged across the sample. These global weights indicate the overall perceived importance of each factor.

Once each expert has a full weight vector:

- For each factor j , compute:

$$\text{Global Average Weight for } j = \frac{1}{E} \sum_{e=1}^E w_j^{(e)}$$

Where:

- E = number of experts
- $w_j^{(e)}$ = weight assigned to factor j by expert e

This concludes to a **ranking** of all factors. The results were presented using radar charts.

3.5.2. Interpretation

After obtaining the aggregated weights for each DOA, a separate analysis was conducted focusing on the interpretation of factor prioritization within each autonomy level. Finally, a comparison across DOA was conducted to highlight how the relative importance of factors shifted and evolved.

The flowchart (Figure 3.1) presents analytically the steps of the Best-Worst Method being followed to get to the results and the calculation of the global weights.

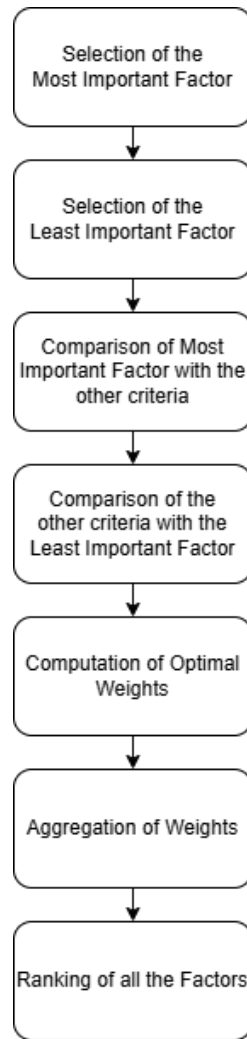


Figure 3.1: Steps of BWM & Ranking of Factors

3.6. Ranking Questions

To answer the final sub-research question regarding the segments most likely to adopt MASS first based on vessel types and sailing routes, ranking questions were included in the last section of the survey. These were analyzed using the Borda's Method [117], to identify collective preferences among participants and the results were presented using donuts charts.

Several ranking methods were considered for this study, including simple ranking, paired comparison, and the rank sum method. However, Borda's Method (or Borda Count) was selected because it captures and aggregates each respondent's complete preference ranking. The Borda Count is a ranking-based voting and decision-making method that transforms ordinal rankings into numerical scores, allowing researchers to determine which options are the most preferred overall. It is widely used in survey analysis, group decision-making and multi-criteria evaluation, where participants rank multiple options.

In Borda's Method, each respondent ranks all available options from most to least preferred. Points are then assigned to each option based on its position in the ranking, with higher ranks receiving more points. These points are referred to as Borda scores, and the option with the highest total score across all respondents is considered the group's most preferred.

General Scoring Rule

Given:

- n = total number of options

- r = rank assigned by a respondent (where $r = 1$ is the highest rank)

The Borda score for a given rank is calculated as:

$$\text{Score} = n - r + 1 \quad (3.4)$$

This means:

- The highest-ranked option receives n points
- The second-highest receives $n - 1$ points
- ...
- The lowest-ranked option receives 1 point

Aggregation of Scores

Let:

- k = total number of respondents
- Score_i = Borda score assigned to a given option by respondent i

The total Borda score for that option is calculated as:

$$\text{Total score} = \sum_{i=1}^k \text{Score}_i \quad (3.5)$$

After all individual rankings are converted into Borda scores and aggregated, the options are sorted in descending order based on their total scores. The option with the highest total score is considered the most collectively preferred, followed by the next highest, and so on.

For the question "Which types of routes are most likely to see early adoption of autonomous vessels in the industry?", respondents ranked three options: trans-ocean, coastal (short-sea), and inland. The first-ranked option was scored as 3, their second-ranked as 2, and their third-ranked as 1.

Similarly, for the question "Which vessel types are most likely to adopt autonomous technologies first in the commercial maritime industry?", five vessel types were ranked: bulk carriers, containerhips, tankers, general cargo vessels, and Ro-Ro vessels. In this case, the first-ranked option was awarded 5 points, decreasing sequentially to 1 point for the lowest-ranked option.

3.7. Multiple-Choice Questions

The survey included several multiple-choice questions designed to gather structured responses on specific aspects of MASS adoption. These questions aimed to assess feasibility and likelihood of adoption.

Participants responded to the following questions:

"Do you think your previous responses about the importance of factors would change depending on the route or type of vessel?"

"Which autonomy level do you consider most feasible for operational deployment by your company?"

"How likely is it that your company would adopt a vessel at the level you considered to be most feasible?"

Responses to these questions were analyzed by calculating response percentages for each option. This approach allowed for a clear presentation of how preferences and expectations were distributed across the sample, providing additional context for interpreting the overall results of the study. The results were presented using percentages and pie charts.

3.8. Open-Ended Questions

The survey also included open questions to gather qualitative information on MASS adoption and to clarify the multiple choice selections of respondents, specifically about changes in responses on the importance of factors. These responses were analyzed to identify common themes and differing opinions. Direct quotations from participants were used to highlight key themes and add context to our findings.

All the questions can be found in the last part of the questionnaire in Appendix D.

3.9. Data Collection

Data were collected using an online questionnaire administered through the Qualtrics platform. It was distributed between May and June of 2025. The survey targeted maritime professionals, including shipping managers, executives, advisors and engineers, via direct email invitations and through a networking platform. The BWM data collection survey differs from standard Likert-scale questionnaires by asking respondents to make pair-wise comparisons between the most (Best) important and least (Worst) important factors. In addition to the main BWM exercise, the survey included a few supplementary questions designed to gather expert views on the practical deployment of autonomous technologies, such as likely levels of autonomy, suitable trade routes and types of vessels expected to adopt these innovations first.

The questionnaire was divided into clear sections to guide respondents through each step:

Section 1: Initially the questionnaire began with a welcome screen that explained the study's purpose ("Navigating Autonomy: Factors Affecting Adoption of Autonomous Vessels"), estimated completion time (about 10 minutes), and the institution conducting it (TU Delft). Respondents were informed that their answers would remain confidential and used only in aggregated form. They were presented with an informed-consent statement outlining the study's goals, data storage, and confidentiality.

Section 2: Then participants were asked about professional details. Company name, role, managerial status, years of maritime experience, vessel types they had worked with, and familiar trade routes. Simple multiple-choice or checkbox questions to keep things easy were used.

Section 3: The key factors of the study and the different degrees of autonomy were explained to the participants. This section prepared respondents for the main Best–Worst Method (BWM) questions.

Section 4 to 6: In these sections, respondents ranked the factors for each of the three different degrees of autonomy. The steps of the Best–Worst Method are described in the following section.

Section 7: Participants ranked which autonomy level they thought was most feasible for their organization, using a drag-and-drop interface. They also ranked trade routes (Coastal/Short-sea, Inland, Trans-ocean) and vessel types (Bulk Carriers, Containerships, Tankers, General Cargo Vessels, Ro-Ro Vessels) that are likely to adopt autonomous technologies first. A yes/no question then asked if their earlier rankings would change based on route or vessel type. Furthermore, they were asked how likely their company would be to adopt the chosen autonomy level, using a three-point scale ("Not likely," "Likely," "Not sure").

Furthermore, participants completed open-ended questions about the adoption of MASS, and their responses, used as direct quotations, provided qualitative insights to illustrate key perspectives.

By organizing the questionnaire into these sequential sections, the survey ensured respondents understood each concept before making choices. This structure captured both the quantitative BWM data and valuable qualitative insights on practical deployment. The full questionnaire can be found in Appendix D.

Analysis & Results

4.1. Factors for MASS Adoption

The factor "Economic and Business Advantages" includes all the possible benefits a shipowner could have with the adoption of MASS as they can directly impact profitability, operational efficiency, and business sustainability in the maritime industry. This factor covers profitability gains from cutting crew costs and increasing cargo capacity, as well as opening up new business opportunities. Additionally, MASS improve fuel efficiency, schedule reliability, and cuts operational costs by using real-time data and optimizing asset use. These economic gains also support environmental goals by lowering fuel use and emissions.

The factor "Investment, Development, and Operational Costs" includes all possible costs related to the adoption of MASS. Experts suggested not to break down this factor into more specific costs (i.e. CAPEX, OPEX, VOYEX, ...), as we are in an early stage of the development and adoption of MASS, thus it could be compared with the other factors as a whole. It covers costs of initial R&D, such as prototyping and integrating advanced autonomous technologies, sensors, and cybersecurity systems. It also covers the economic considerations between new-build and retrofitted ships. This factor further includes long-term expenses like training remote-control operators, maintaining autonomous systems, staffing control centers, and ensuring constant connectivity.

"Insurance & Premiums" is selected as it plays a key role in managing risk. MASS adoption will lead to significant changes in traditional insurance frameworks, especially regarding higher levels of autonomy. As there are many limitations in historical data, evolving risk profiles, and uncertainties regarding liability, this can affect widespread adoption of autonomous vessels. It includes aspects of availability of insuring ships against operational risks and potential liabilities, and risk-sharing models tailored to MASS operations.

"Vessel's Technological Maturity and Reliability" is a really important factor due to its direct influence on safety, commercial acceptance, and overall operational effectiveness MASS. This factor includes all different aspects of the maturity and reliability of the technologies of an autonomous vessel that have also been identified by other studies. Such technologies are navigation and anti-collision systems, communication networks, and cybersecurity frameworks that have already been identified as important in previous studies [13]. This factor also highlights the need for user-friendly, reliable human-machine interfaces, both onboard and shore-based, to improve operator decision-making and situational awareness. Also, focusing on cybersecurity and physical threats, it underscores the requirement for systems that can effectively address these risks.

The factor "Port Infrastructure Readiness" is another significant factor as it can facilitate adoption of MASS. It focuses on the availability and implementation of smart-port infrastructure such as automated mooring and cargo handling systems, and port related digital shore-control centers, as well as security measures to protect both data integrity and physical infrastructure.

"Standardization" covers the need for common technical standards, such as protocols for data formats,

communication systems, and control interfaces, across all the interconnected subsystems in MASS. The absence of unified technical standards introduces uncertainty in design and operational practices and limits compatibility between autonomous systems. This factor has not yet been extensively studied in MASS adoption and it was suggested by the research team during factor refinement.

"Emergency Response Capability" is another key factor because autonomous vessels, especially those operating without crew onboard, must independently manage a range of high-risk scenarios such as collisions, groundings, and system failures. Without a crew onboard, MASS must use reliable protocols and technologies to detect, assess, and respond to emergencies in real time.

The factor "Human-Capital Readiness" has always been a critical factor in the operations of shipping. The transition to higher levels of autonomy shifts skill requirements from traditional seafaring to remote operation, system diagnostics, and cyber-physical integration. The success of MASS depends on the availability of personnel who are not only trained in maritime navigation and engineering, but also equipped with expertise in IT and data-driven decision making.

Finally, the "Regulatory and Legal Framework" factor is important because it ensures that MASS operate safely and legally on regional and international waters. Current maritime conventions are built around crewed vessels, and changes need to be made to include also uncrewed vessels. Having clear legal rules is essential for assigning liability in the event of accidents and for consistent enforcement across jurisdictions.

The factors and their descriptions are presented in Table 4.1.

Factor	Explanation
Economic and business advantages	Advantages related with improvements in profitability, new business opportunities, fuel efficiency, scheduling reliability and cost savings.
Investment, development and operational costs	Up-front R&D, retrofit/build costs, training and ongoing operational costs.
Insurance & premiums	Availability of insuring ships against operational risks and potential liabilities, and risk-sharing models tailored to MASS operations.
Vessel's technological maturity and reliability	Availability of mature technologies and systems that are reliable and resilient. I.e. navigation and anti-collision, communication and cyber and physical security systems. Ease of use of human-machine interfaces on vessels and shore-control centers.
Port infrastructure readiness	Availability of smart-port features (automated berths, digital shore-control centers) plus port-side security measures (secure data links, access controls, anti-tamper systems).
Standardization	Well-defined technical standards (e.g. data formats, control interfaces) that reduce integration risk.
Emergency response capability	Protocols and systems for collision, grounding, or system-failure scenarios of vessels.
Human-capital readiness	Availability of training programs and skilled personnel for MASS operations (shore-crew upskilling, certifications, cross-disciplinary expertise).
Regulatory and legal framework	Clarity and completeness of IMO and flag-state rules (e.g. SOLAS, COLREGS, MARPOL) for unmanned operation, including legal responsibility in case of accidents.

Table 4.1: Key factors influencing MASS adoption

4.2. Sample Characteristics

Our expert panel included 20 respondents which have extensive experience in a broad range of shipping functions. As the focus of the study is to understand the perspectives of shipowners and shipping

companies, the focus was not pure autonomy specialists. Out of those 20 responses received, 3 were incomplete and 3 assigned equal importance to all factors, making them unsuitable for use in the BWM analysis. That left 14 valid BWM surveys for our weight calculations. However, we did consider the 17 fully filled-out responses when drawing broader conclusions. Before the main roll-out, we conducted a small pilot with three industry experts to help us clarify a few survey items. Their pilot responses were excluded from the final analysis. Our final sample of 14 experienced professionals provides reliable insights into how shipowners view key factors at each autonomy level. The characteristics of the experts can be found in Table 4.2.

Res	Position	Affiliation	Exp. (years)
1	Managing Director	Industry-commercial	40
2	Tanker Operator	Industry-commercial	10
3	Director Marine & Operations	Industry-commercial	27
4	DPA	Industry-commercial	17
5	Marine Engineer	Industry-technical	5
6	EVP Green Energy & Technology	Industry-commercial	44
7	Manager Compliance	Industry-commercial	40
8	Chartering	Industry-commercial	12
9	Environmental Compliance Engineer	Industry-technical	8
10	Product Manager USV	Industry-technical	14
11	Chartering Manager	Industry-commercial	30
12	Post Fixture Manager	Industry-commercial	22
13	Maritime Technology Advisor	Industry-technical	9
14	Logistics Coordinator	Industry-commercial	20

Table 4.2: Industry professionals' positions, affiliations, and experience

The respondents to the survey have an average of 21 years of professional experience, with a range spanning from 5 to 44 years. In particular, 71% (Figure 4.1) of these individuals hold managerial positions, highlighting a strong representation of leadership roles within the sample. Their operational backgrounds cover a diverse range of vessel types: 79% have experience with bulk carriers, 57% with containerhips, 43% with general cargo vessels and 36% each with tankers and Ro-Ro vessels (Figure 4.2). In terms of navigational routes, 79% have worked on trans-ocean operations, 43% on coastal or short-sea routes, and 21% on inland waterways (Figure 4.3). This indicates a workforce with both broad and deep exposure across vessel types and shipping routes.

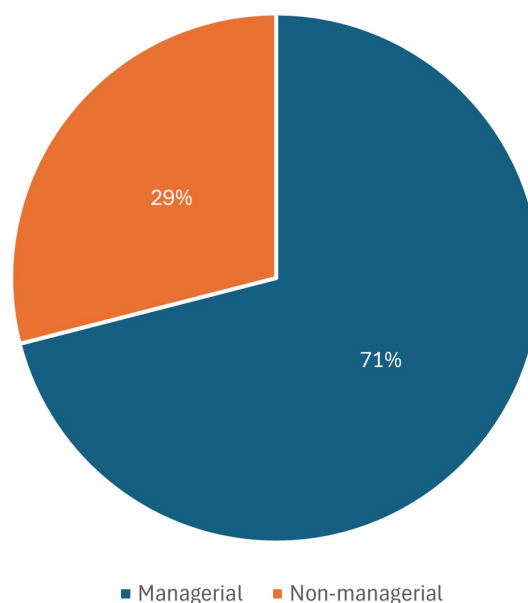


Figure 4.1: Distribution of managerial roles among respondents

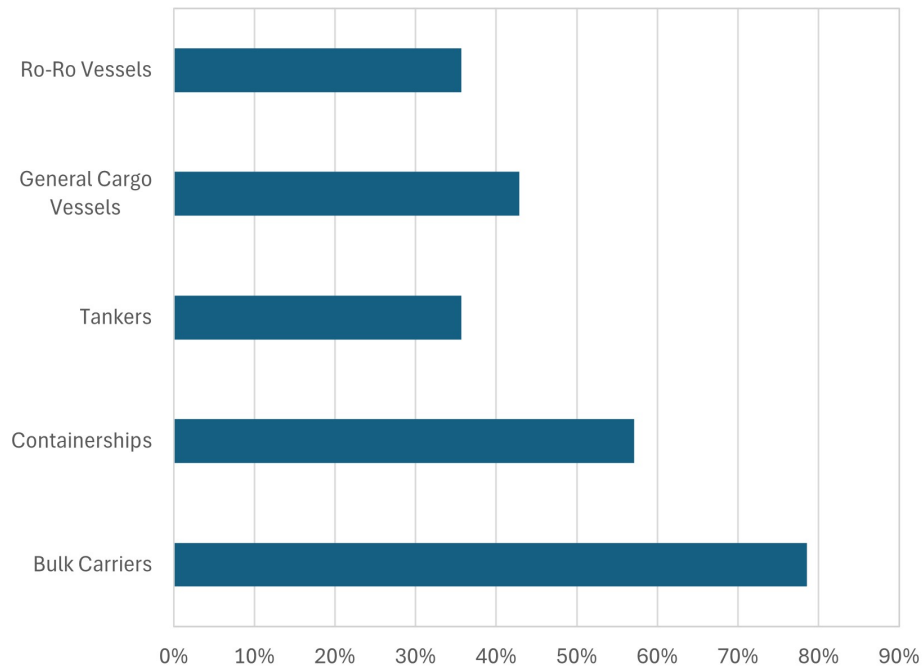


Figure 4.2: Respondents' operational experience by vessel type

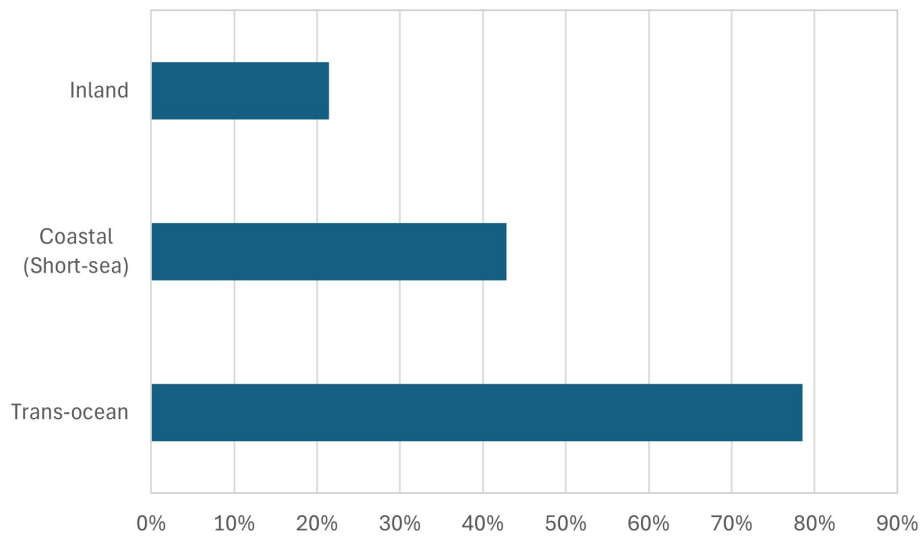


Figure 4.3: Respondents' operational experience by routes

4.3. BWM Weight Computation

For each autonomy level (DOA 2, DOA 3, DOA 4), we identified the “best” (most important) and “worst” (least important) factors, collected pairwise comparisons of best vs. each other factor, and each factor vs. worst and solved the linear programming model to derive a weight for each of the nine factors. Furthermore, for each expert and each DOA level, the consistency ratio (CR) was calculated. Finally for the different autonomy levels the global averages were calculated to get to the final ranking.

4.3.1. Degree of Autonomy 2 (Remotely Controlled Ships with Crew)

At DOA 2, Investment, Development & Operational Costs (0.148) and Economic & Business Advantages (0.146) are the highest-ranked factors. This indicates that shipping companies mainly evaluate this level of autonomy based on its financial feasibility, costs, and expected economic benefits. Emergency

Response Capability (0.120) is the next, which highlights concerns regarding safety systems, as new technologies can introduce unfamiliar emergency scenarios. Vessel Technological Maturity & Reliability (0.115) ranks slightly lower, which may reflect the perception that at DOA 2, technological failures are still manageable due to human presence. The middle range includes Regulatory & Legal Framework (0.108) and Human-Capital Readiness (0.104), suggesting moderate importance as companies begin considering the regulatory environment and crew training. The least important at this level are Port Infrastructure Readiness (0.094), Standardization (0.086), and Insurance & Premiums (0.079), showing these are viewed as less critical for adoption.

We present in Table 4.3 each respondent's optimal criterion weights along with their consistency ratio (CR). Because BWM's consistency ratio is outcome-driven, values up to 0.3662 are deemed acceptable for nine criteria. In our study and for DOA2 the average CR is 0.138, and no respondent exceeds the acceptable limit. Radar chart (Figure 4.4) shows the average weights for all nine factors, giving a quick view of how important each one is at this autonomy level.

The complete Best-to-Others and Others-to-Worst comparison matrices for DOA2 are provided in Appendix A.

Res	F1	F2	F3	F4	F5	F6	F7	F8	F9	CR
1	0.258	0.070	0.070	0.070	0.130	0.018	0.088	0.117	0.176	0.097
2	0.071	0.341	0.128	0.092	0.041	0.071	0.071	0.092	0.092	0.361
3	0.054	0.331	0.042	0.054	0.143	0.094	0.125	0.125	0.033	0.000
4	0.341	0.082	0.030	0.051	0.082	0.059	0.068	0.082	0.205	0.069
5	0.054	0.054	0.075	0.094	0.025	0.075	0.300	0.250	0.075	0.292
6	0.107	0.271	0.107	0.107	0.080	0.032	0.107	0.080	0.107	0.119
7	0.059	0.059	0.074	0.218	0.183	0.149	0.149	0.035	0.074	0.214
8	0.202	0.178	0.080	0.080	0.060	0.023	0.080	0.178	0.120	0.071
9	0.273	0.126	0.231	0.063	0.054	0.094	0.076	0.063	0.021	0.000
10	0.095	0.095	0.021	0.142	0.036	0.235	0.071	0.071	0.235	0.000
11	0.188	0.126	0.042	0.188	0.054	0.126	0.075	0.075	0.126	0.083
12	0.108	0.160	0.013	0.202	0.160	0.160	0.108	0.022	0.067	0.083
13	0.199	0.121	0.121	0.121	0.081	0.031	0.121	0.081	0.121	0.250
14	0.041	0.053	0.074	0.123	0.184	0.038	0.241	0.184	0.061	0.292
Mean	0.146	0.148	0.079	0.115	0.094	0.086	0.120	0.104	0.108	0.138

Table 4.3: Optimal criterion weights and input-based consistency ratios (CR) for each respondent for DOA2

The highest weight of each respondent is indicated with bold.

F1: Economic and business advantage, F2: Investment, development and operational costs, F3: Insurance & premiums, F4: Vessel's technological maturity and reliability, F5: Port infrastructure readiness, F6: Standardization, F7: Emergency response capability, F8: Human-capital readiness, F9: Regulatory & legal framework.

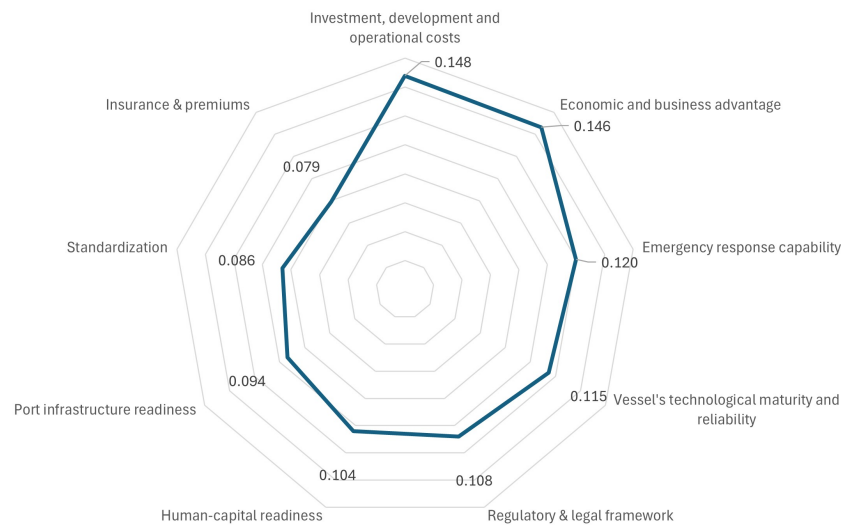


Figure 4.4: Average weights across all nine factors for DOA2

4.3.2. Degree of Autonomy 3 (Remotely Controlled Ships without Crew)

At Degree of Autonomy 3, the priorities shift significantly. Vessel Technological Maturity & Reliability rises to first place (0.197). Removing crew from ships makes reliability and maturity of technology the primary concern. The second and third most important factors are Regulatory & Legal Framework (0.128) and Emergency Response Capability (0.123), underscoring the growing importance of clear regulations, liability management, and autonomous safety protocols. Investment & Operational Costs (0.122) remains relevant, while Human-Capital Readiness (0.104) and Economic Advantages (0.099) have slightly decreased in priority. Insurance & Premiums (0.085), Standardization (0.072), and Port Infrastructure Readiness (0.070) remain lower-ranked. Stakeholders may see these as something that will follow once technology and legal standards are established.

In Table 4.4 each respondent’s optimal criterion weights along with their consistency ratio (CR) are presented. Because BWM’s consistency ratio is outcome-driven, values up to 0.3662 are deemed acceptable for nine criteria. For DOA3 the average CR is slightly increased to 0.162, and no respondent exceeds the acceptable limit. A complementary radar chart (Figure 4.5) shows the average weights for all nine factors, giving a quick view of how important each one is at this autonomy level.

The complete Best-to-Others and Others-to-Worst comparison matrices for DOA3 are provided in Appendix B.

Res	F1	F2	F3	F4	F5	F6	F7	F8	F9	CR
1	0.061	0.085	0.053	0.298	0.047	0.019	0.212	0.085	0.141	0.250
2	0.034	0.049	0.049	0.244	0.081	0.027	0.027	0.244	0.244	0.111
3	0.109	0.087	0.062	0.062	0.062	0.109	0.145	0.145	0.218	0.071
4	0.106	0.141	0.053	0.349	0.060	0.060	0.060	0.031	0.141	0.167
5	0.071	0.054	0.048	0.214	0.043	0.071	0.214	0.214	0.071	0.100
6	0.110	0.110	0.082	0.271	0.082	0.042	0.082	0.110	0.110	0.200
7	0.027	0.043	0.054	0.175	0.215	0.175	0.175	0.043	0.094	0.050
8	0.106	0.106	0.106	0.174	0.070	0.015	0.159	0.106	0.159	0.014
9	0.061	0.143	0.086	0.143	0.054	0.071	0.214	0.086	0.143	0.036
10	0.095	0.095	0.022	0.143	0.041	0.219	0.071	0.219	0.095	0.262
11	0.209	0.279	0.110	0.209	0.037	0.018	0.037	0.047	0.055	0.292
12	0.028	0.254	0.254	0.254	0.051	0.051	0.028	0.028	0.051	0.222
13	0.199	0.121	0.121	0.121	0.081	0.031	0.121	0.081	0.121	0.250
14	0.176	0.142	0.095	0.095	0.057	0.095	0.176	0.023	0.142	0.250
Mean	0.099	0.122	0.085	0.197	0.070	0.072	0.123	0.104	0.128	0.162

Table 4.4: Optimal criterion weights and input-based consistency ratios (CR) for each respondent for DOA3

The highest weight of each respondent is indicated with bold.

F1: Economic and business advantage, F2: Investment, development and operational costs, F3: Insurance & premiums, F4: Vessel's technological maturity and reliability, F5: Port infrastructure readiness, F6: Standardization, F7: Emergency response capability, F8: Human-capital readiness, F9: Regulatory & legal framework.

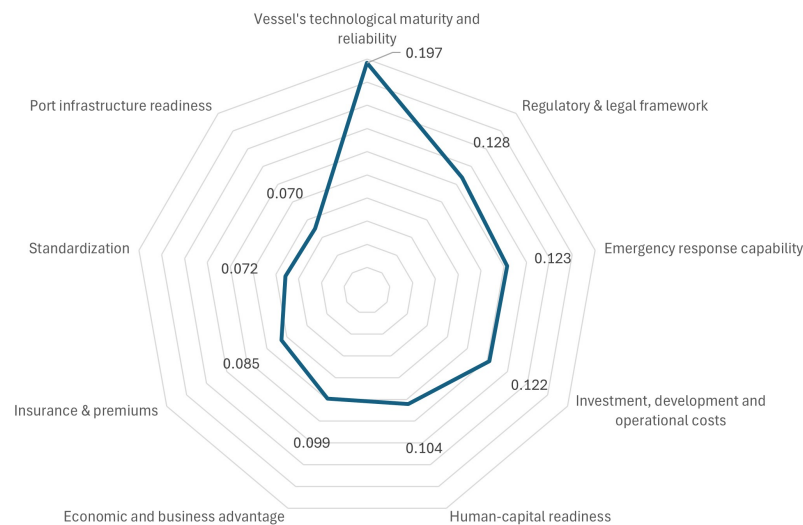


Figure 4.5: Average weights across all nine factors for DOA3

4.3.3. Degree of Autonomy 4 (Fully Autonomous)

At full autonomy (Degree of Autonomy 4), Vessel Technological Maturity & Reliability remains the top-ranked factor (0.169). The high weight reflects ongoing concerns about whether current technologies can reliably and safely support this level of autonomy in all maritime conditions. Regulatory & Legal Framework significantly increases in importance, closely behind at second place (0.145). The complexity of regulations, combined with the absence of onboard crew, makes clear legal guidelines especially important. Emergency Response Capability (0.135) remains a key concern, highlighting ongoing worries about safety and the effectiveness of autonomous emergency procedures. Human-Capital Readiness (0.111) slightly increases due to the necessity for skilled shore-based operators. Economic & Business

Advantages (0.110) and Investment & Operational Costs (0.093) drop further in importance compared to earlier DOA levels. Respondents see DOA 4 as a transformation that depends first on system and institutional readiness. Insurance & Premiums (0.084), Port Infrastructure Readiness (0.079), and Standardization (0.075) remain at the lower end of the ranking. These results suggest that while these factors are not insignificant, they are viewed as more manageable once the key challenges are resolved.

In Table 4.5 each respondent's optimal criterion weights along with their consistency ratio (CR) are presented. For DOA4 the average CR is 0.155. In this case we had a response that exceeded the acceptable limit and the response was not included for the calculation of the optimal weights. Radar chart (Figure 4.6) shows the average weights for all nine factors, giving a quick view of how important each one is at this autonomy level.

The complete Best-to-Others and Others-to-Worst comparison matrices for DOA4 are provided in Appendix C.

Res	F1	F2	F3	F4	F5	F6	F7	F8	F9	CR
1	0.054	0.054	0.054	0.048	0.048	0.028	0.048	0.231	0.434	0.000
2	0.083	0.153	0.153	0.153	0.153	0.135	0.135	0.022	0.013	0.143
3	0.108	0.090	0.090	0.108	0.068	0.090	0.108	0.068	0.270	0.000
4	0.104	0.087	0.065	0.403	0.065	0.065	0.074	0.032	0.104	0.361
5	0.067	0.026	0.140	0.067	0.025	0.067	0.202	0.202	0.202	0.018
6	0.106	0.106	0.106	0.260	0.064	0.040	0.106	0.106	0.106	0.200
7	0.038	0.038	0.038	0.256	0.154	0.154	0.256	0.026	0.038	0.143
8	0.101	0.101	0.101	0.162	0.067	0.015	0.177	0.101	0.177	0.018
9	0.125	0.083	0.062	0.100	0.071	0.083	0.125	0.250	0.100	0.304
10	0.103	0.103	0.022	0.103	0.062	0.154	0.077	0.228	0.148	0.089
12	0.233	0.146	0.028	0.233	0.088	0.088	0.049	0.049	0.088	0.222
13	0.198	0.119	0.119	0.119	0.119	0.032	0.119	0.059	0.119	0.250
14	0.108	0.108	0.108	0.185	0.046	0.023	0.277	0.065	0.081	0.264
Mean	0.110	0.093	0.084	0.169	0.079	0.075	0.135	0.111	0.145	0.155

Table 4.5: Optimal criterion weights and input-based consistency ratios (CR) for each respondent for DOA4

The highest weight of each respondent is indicated with bold.

F1: Economic and business advantage, F2: Investment, development and operational costs, F3: Insurance & premiums, F4: Vessel's technological maturity and reliability, F5: Port infrastructure readiness, F6: Standardization, F7: Emergency response capability, F8: Human-capital readiness, F9: Regulatory & legal framework.

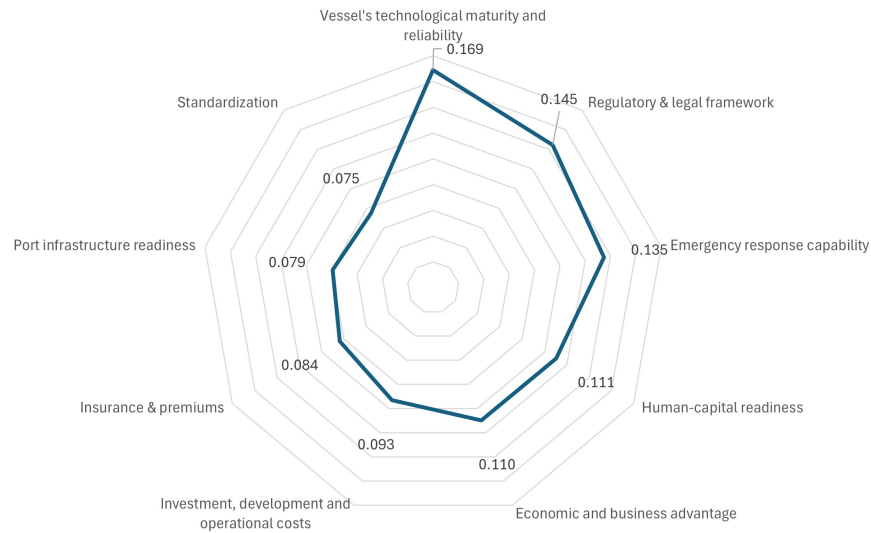


Figure 4.6: Average weights across all nine factors for DOA4

4.4. Comparative Analysis Across DOA Levels

At DOA 2, decision-making is mainly driven by factors with immediate financial impact, such as Investment, Development & Operational Costs (0.148), and Economic & Business Advantages (0.146). At this stage, vessel technologies can be maintained and technical issues can be resolved by onboard crew. Companies see autonomy more as a way to increase performance than as a transformative change, and their decision to adopt is still based on economic feasibility. This aligns with findings in the maritime adoption literature, where early-stage technology adoption is primarily cost-driven and cautious due to financial uncertainties [6, 13].

However, as autonomy increases to DOA 3, the focus shifts significantly towards ensuring reliable and mature technological systems. Vessel Technological Maturity and Reliability becomes the top-ranked factor (0.197), highlighting the crucial need for trustworthy technology in fully uncrewed vessels. With no onboard crew to handle operational issues, companies must have total confidence in sensors, artificial intelligence, collision-avoidance systems, and remote communication reliability. This aligns with previous studies indicating that the industry views technological reliability as essential for accepting and deploying higher levels of autonomy [13, 30, 32].

By the time full autonomy (DOA 4) is reached, regulatory concerns become even more important. The Regulatory & Legal Framework steadily increases from 0.108 (DOA 2) to 0.145 (DOA 4). At this fully autonomous level, shipping companies worry about unclear rules, liability questions, and compliance issues. Clear regulations and laws help shipowners feel more secure, lowering their perceived risks. However, Vessel Technological Maturity & Reliability (0.169) is still the most important factor in full autonomy. This shows that shipping companies need proven, reliable technology before they can fully trust autonomous operations, even when there are clear rules. Existing research also shows that both reliable technology and clear regulations are essential for fully autonomous vessels to become widely used [68, 99]. While Economic & Business Advantages (0.110) and Investment & Operational Costs (0.093) continue to be considered, they become longer-term strategic concerns rather than immediate decision drivers.

Across all three autonomy levels, Emergency Response Capability increases from 0.120 (DOA 2) to 0.135 (DOA 4). This progression highlights ongoing safety concerns and the need for effective autonomous emergency protocols when crews are no longer onboard. Previous research supports these findings, showing how emergency handling affects the adoption decision, particularly at higher autonomy levels where human intervention is not easy or possible [14, 30, 95, 96].

Human-Capital Readiness remains relatively stable (0.104–0.111) across autonomy levels, showing persistent recognition of the need for skilled shore-based personnel to operate remotely controlled and fully autonomous vessels. Studies have repeatedly highlighted the need for specialized training, remote operation skills, and integrated expertise to manage these advanced systems effectively from shore-based facilities. [47, 96].

Finally, Insurance & Premiums, Port Infrastructure Readiness, and Standardization maintain lower priorities at all autonomy levels. These factors, while necessary, are seen as concerns, more easily resolved once core technological, regulatory, and safety issues have been effectively addressed. Existing research supports this view, suggesting that although these enabling factors are essential for widespread adoption, shipping companies perceive them as more manageable or lower-risk after successfully navigating the primary barriers of autonomy adoption [30, 39, 91].

Figure 4.7 summarizes these shifts in priorities across different degrees of autonomy.

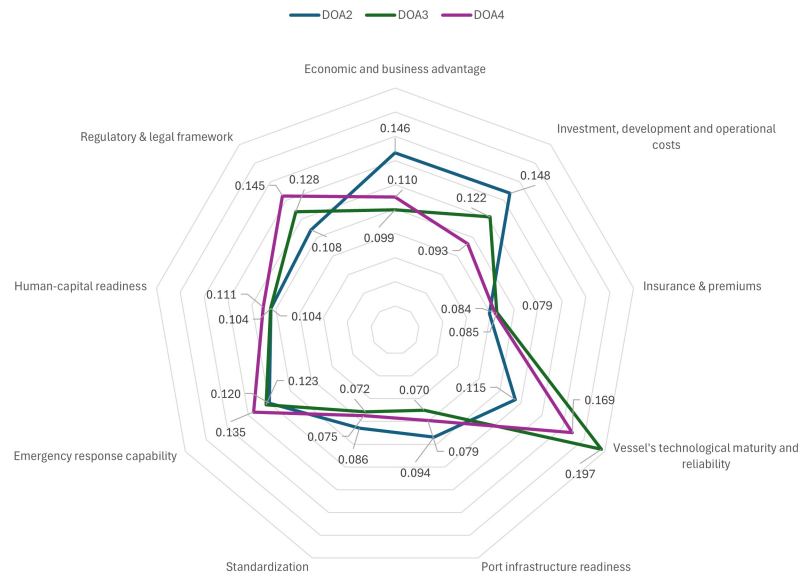


Figure 4.7: Average weights across all nine factors and degrees of autonomy

4.5. Ranking Questions

To answer the last sub-research question, respondents ranked three route types: inland, coastal (short-sea), and trans-ocean. Inland routes were identified as the most likely to adopt autonomous vessels early, with 40% preference. This aligns with current industry developments, such as Zulu Associates, which already operates autonomous vessels on inland waterways, demonstrating practical feasibility [118]. Coastal routes follow closely at 35%, while trans-ocean routes are considered the least likely, at 25%. Figure 4.8 shows the distribution of respondents' rankings regarding route adoption.

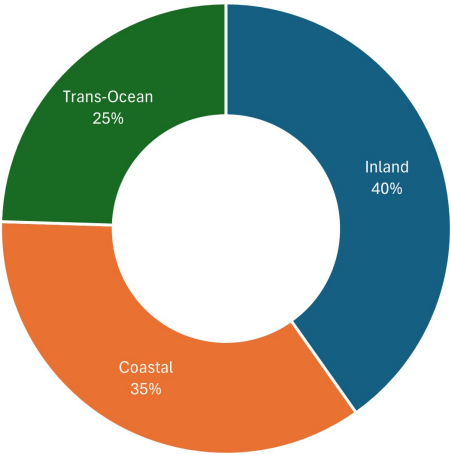


Figure 4.8: Routes most likely to adopt autonomous vessels first.

Furthermore, respondents ranked five vessel types regarding their likelihood to adopt autonomy first: containerships (28%), Ro-Ro vessels (21%), bulk carriers (20%), general cargo vessels (17%), and tankers (14%). Figure 4.9 summarizes the overall industry preferences. This ranking aligns with current examples, such as the Yara Birkeland, a fully autonomous containership that already operates commercially in Norway [36]. Containerships and Ro-Ro vessels lead due to their predictable routes, regular schedules, and potential operational efficiency gains from autonomy.

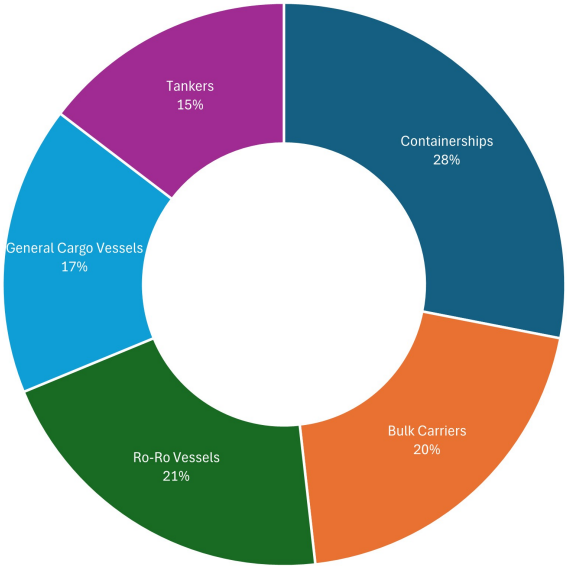


Figure 4.9: Vessel types most likely to adopt autonomous technologies first.

4.6. Multiple-Choice and Open-Ended Questions

When participants were asked about the most feasible degree of autonomy for operational deployment, a clear majority (76%) considered DOA 2 (remotely controlled vessels with crew onboard) as the most realistic initial step. Only 24% saw DOA 3 (remotely controlled without onboard crew) as immediately feasible (Figure 4.10). This indicates a cautious industry approach, preferring slow and steady steps towards autonomy while maintaining crew presence onboard during initial stages to ensure operational

reliability and safety.

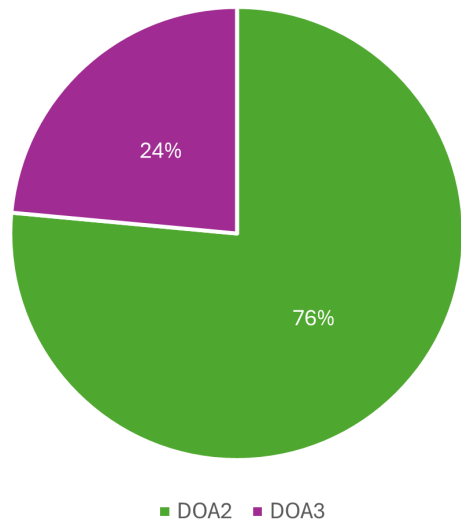


Figure 4.10: Most feasible degree of autonomy for operational deployment.

when asked how likely their company was to adopt the identified feasible level, only 24% said adoption was likely, while 41% said not likely, and 35% were unsure. These responses suggest a cautious approach, reflecting industry uncertainty around practical implementation, regulatory frameworks, and investment risks despite recognizing technological feasibility (Figure 4.11).

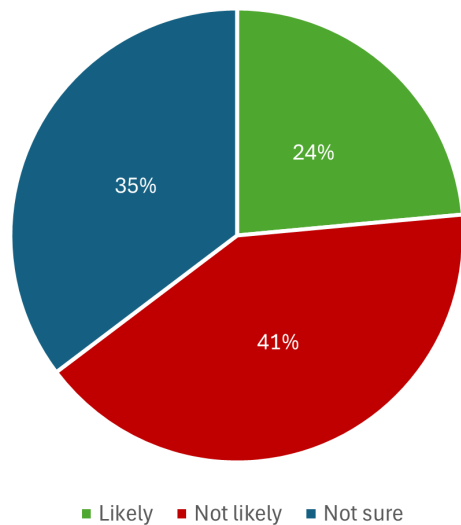


Figure 4.11: Likeliness of adopting the most feasible degree of autonomy previously identified.

Four respondents while choosing "Not likely" as an option filled out an open-ended question explaining further their preference.

Several participants expressed a preference for DOA 2, citing its balance between automation and human oversight. They emphasized the importance of retaining onboard personnel for tasks like maintenance, monitoring, and intervention:

"Remotely controlled with minimum crew onboard."
"Degree 2, because it would give the ability to onshore personnel to command the ships with their expertise more easily, while keeping the onboard personnel, mostly for monitoring, reporting, and intervention (by following

onshore personnel's troubleshooting guidance)."

"Degree of Autonomy 2 because ships will need maintenance during trading."

Some respondents indicated that MASS adoption is unlikely or currently unfeasible for their company due to practical limitations:

"For our company, autonomous shipping is likely a premature concept."

"We're not the owners of the vessel and the countries which we are serving are not (yet) as developed as most western countries."

Additionally, a question was asked to understand whether the prioritization of adoption factors would change depending on the type of vessel and route. Slightly more than half (53%) said yes, while 47% said no, indicating a disagreement between the respondents. Analyzing further these percentages, of the respondents who hold management positions, 64% replied yes, while 36% replied no. However, of the respondents not in management positions, only 17% (1 out of 6) and the rest 83% replied no.

To better understand this preference, respondents filled out an open-ended question. This question was filled out by six experts, all in management positions, who chose yes as their previous answer.

Multiple respondents emphasized that different routes involve distinct operational, environmental, and safety-related conditions that influence how factors are prioritized. This includes considerations such as sea states, local knowledge, and the nature of the route itself:

"Each route poses different threats and opportunities, therefore these affect the dynamic between the factors."

"Variability and dynamics of risks and benefits of maritime routes could cause changes in responses."

"Certainty of navigation, nature of sea states. Also port infrastructure."

"A fixed route autonomy can be made more safe in a shorter period due to 'local knowledge', same as with pilot exemption when frequently visiting a port."

Respondents noted the importance of automated systems and port infrastructure in shaping feasibility and adoption:

"Automated cargo handling processes are key in combination with readiness of the ports."

(from earlier response) "Also port infrastructure."

"The adoption of these vessels will be heavily influenced by the safety requirements of ports as this is the point whereby infrastructure becomes the predominant factor."

These results show the maritime industry's careful but growing interest in autonomous vessels. DOA 2 is considered the most practical first step, but concerns about regulations, infrastructure, and operational risks slow down near-term adoption.

5

Discussion

5.1. Factors Affecting MASS Adoption

Based on the finding of chapter 4 at DOA 2, where ships are remotely controlled but still crewed, the highest-ranked factors are Investment, Development & Operational Costs (0.148) and Economic & Business Advantages (0.146). This result is closely aligned with existing research [6, 12–14], which highlights the importance of economic considerations during early adoption phases. In studies on the adoption of MASS in different settings, operational and capital expenditures rank as top factors affecting adoption [12, 13]. Shipping companies typically adopt innovations cautiously due to financial uncertainties, as this sector has inherent risks [6]. However, based on our findings, these factors are specifically important for DOA 2, a detail less discussed in prior literature. Human presence on board acts as a safety net, reducing the immediate relevance of regulatory or technical barriers.

Regarding DOA 3 and DOA 4, economic factors, whether the benefits or costs, rank lower in importance. In support of this finding, an expert stated for higher degrees of autonomy that economics is not the goal, as there are other priorities to be addressed:

"Economics has no priority in this, it will be a result of rather than a goal. Safety of people, environment and cargo need to be secured. Education of people, automation of processes, and emergency response time are the most important aspect to be secured."

Moving towards higher autonomy levels (DOA 3 and DOA 4), Vessel Technological Maturity & Reliability becomes the top concern (DOA 3: 0.197, DOA 4: 0.169). This finding supports Munim et al.'s result that navigation anti-collision systems and cybersecurity risks, both aspects of technological maturity, significantly influence adoption decisions [13]. Additionally, technological readiness and reliability have been repeatedly highlighted as important for safe and uncrewed vessel operations in different maritime environments [14, 81]. Without crew to manage emergencies or intervene in real-time, the responsibility for safety, continuity, and performance shifts entirely to remote operators and onboard automated systems or to the vessel itself.

A steady increase is observed in the importance of the the Regulatory & Legal Framework across the degrees of autonomy (from 0.108 at DOA 2 to 0.145 at DOA 4). Existing research indicates that clear regulations are key to the commercial success of autonomous shipping [14, 45]. Furthermore, insights from an expert highlighted crucial regulatory gaps, stating:

"We operate ships carrying dangerous cargo in international routes. There is no legislation to support worldwide operations of unmanned ships of this kind."

The emergency response capability factor holds the third position of importance in all degrees of autonomy. Ho and Lee [14] have also identified it as one of the most important factors overall, and Alamoush et al. [30] emphasize the significant concerns around safety and emergency handling as autonomy increases. This was also pointed out by an expert, as mentioned previously. Our research further confirms that autonomous emergency protocols and the ability to manage incidents remotely

are very important for adoption. Although Human-Capital Readiness ranks mid-range among factors, it remains consistent across autonomy levels (0.104–0.111). Fonseca et al. emphasize that human capital, and the training of that workforce, is critical for successful autonomy implementation [40]. This is also supported by previous quote from our expert.

Interestingly, factors such as Insurance & Premiums and Port Infrastructure Readiness remain consistently lower-ranked across autonomy levels. Existing literature [14] also supports this view that these factors, although necessary, are perceived as secondary once technological, regulatory, and safety barriers are resolved. Standardization also ranks low, indicating that unified technical standards are not yet a primary concern for shipowners.

A clear pattern is emerging across the different autonomy levels. Moving to uncrewed operations shifts the focus from business efficiency to trust and safety of the technology. Adoption at this level depends not only on cost-benefit analysis, but also on proven technology reliability and clear regulations. Where the crew onboard DOA 2 can respond to failures and unexpected events, DOA 3 and 4 require predefined legal frameworks, clear accountability protocols, and reliable remote emergency response systems. Technological systems must be tested individually and in combination before they can be trusted for widespread deployment.

Understanding this change requires looking beyond economics. While the maritime industry is undoubtedly profit-driven, the move toward full autonomy introduces a new and unfamiliar risk: removing humans from critical operations. Thus, adoption decisions are increasingly dependent on the perception of risk and the trust in the reliability of the system. Human error is a well-known risk, but stakeholders trust that onboard personnel can mitigate catastrophic failures. This trust reduces perceived risk and makes economic factors, such as business advantages and investment costs, key drivers at earlier autonomy levels.

When human presence is removed, concerns about uncrewed systems lead to psychological and operational uncertainty. From a theoretical point of view, this can be understood through the lens of perceived risk and trust in technology. In innovation adoption research, especially for autonomous systems, trust has been identified as a central factor that can make or break acceptance [119]. Theoretical models such as TAM and UTAUT originally focus on perceived usefulness and ease of use, assuming a baseline level of trust. But in the case of high-autonomy systems, recent research shows that without trust, stakeholders may reject a technology regardless of its benefits. To address this, scholars have adapted models such as UTAUT to explicitly account for trust and risk. Kenesei et al. [120] found that increasing trust and reducing perceived risk can significantly increase perceived benefits of autonomous technology.

Although fully autonomous systems can reduce human error, their complexity introduces new risks, so decision-makers prioritize technological maturity and clear regulations. This resonates with trust theories and risk perception models in technology adoption: people and organizations tend to trust autonomous technology more when there are safeguards or ways to retain control [119]. For example, in the domain of autonomous vehicles, studies have shown that users are more willing to accept self-driving systems if they know that a human can take over and that promoting safety and transparency is essential to build trust [119]. In sum, humans in MASS act as a kind of “risk mitigator” in adoption decisions, and innovation models should include this factor when forecasting adoption of fully autonomous systems.

Finally, it is essential to recognize that analyzing the adoption of MASS requires clear distinctions between different DOA. Researchers should avoid generalizations and explicitly specify which DOA level their analysis addresses, as the influencing factors vary significantly between levels.

5.2. Routes and Vessel Types for Early MASS Adoption

Inland and coastal routes were identified as the most likely for early adoption of autonomous shipping. This also supported by studies suggesting that shorter routes will be more feasible for deployment of MASS [13]. This preference for inland waterways is reflected in real-world examples such as Zulu Associates’ autonomous operations, which demonstrate the technical and logistical viability of autonomous vessels in confined, well-supervised environments [118]. Their shorter distances, calmer sea conditions, and governance under clearly defined national regulatory frameworks make these settings less complex and more manageable for autonomous technologies. According to experts, issues

are likely to be addressed in these settings before expanding to worldwide shipping lanes:

"Legislation and security issues will be earlier addressed in inland routes and non-dangerous cargo ships."

"Apart of reliability of technology for safety, security risks associated with global maritime routes remain greater constraints for early adoption of autonomous vessels."

Especially for trans-ocean shipping, there are many unresolved issues related with high capital costs, emergency response capabilities, legal ambiguities [14] and maintenance of the systems. Specifically, experts who are in trans-ocean companies state that DOA 2 will be the most likely to be adopted in that case:

"Degree 2, because it would give the ability to onshore personnel to command the ships with their expertise more easily, while keeping the onboard personnel, mostly for monitoring, reporting and intervention (by following onshore personnel's troubleshooting guidance)."

"Degree of Autonomy 2 because ships will need maintenance during trading."

Summarizing across different routing segments, trans-ocean shipping may continue to favor DOA 2, where onboard crew can manage long-duration voyages and complex conditions. In contrast, coastal and inland shipping with more predictable environments and easier access to shore-based support may be more aligned with DOA 3 or 4 implementations.

Regarding vessel types, vessels carrying routine cargoes, especially containerships and Ro-Ro vessels, were identified as strong candidates for autonomy due to their standardized operations and high compatibility with smart port systems. This preference is supported by current projects such as the Yara Birkeland [36] and the ASKO autonomous freight carrier [13]. Survey-based projections by Malmquist and Munim [100] suggest that the container and Ro-Ro segments, along with regional passenger ferries and offshore support vessels, are seen as most ready for adoption within a 5–10 year horizon. Additionally, bulk carriers and general cargo vessels rank moderately, probably due to more variable routes and operational complexity, while tankers are least favored.

Overall, the path towards autonomous adoption is likely to vary by sector, shaped by specific operational conditions rather than a one-size-fits-all progression through autonomy levels. There is a clear preference in adopting DOA 2 as the technology readiness is higher than the other DOA, a resolution which is also supported by the AUTOSHIP project, which shows that a Technology Readiness Level (TRL) of 7 or above is needed for technologies to be adopted in the maritime sector [41].

5.3. Patterns across transportation sectors

As the level of autonomy increases across the transportation sectors, there is a significant change in the importance of factors. The shift identified from our research in the maritime industry can also be found in other sectors. If we exclude the space industry, where historically most missions operated robotically without humans, all other transportation sectors have relied on humans testing automation before large-scale deployment. In road transportation, adoption tends to be driven by factors that affect the human operator or passenger directly, especially cost, perceived usefulness, and ease of use (e.g., economic benefits). Having human operators act as a safety net, reducing both perceived and actual risks. Because humans can intervene, regulators and operators are willing to accept less mature technologies. When no human is onboard, concerns shift to the underlying technology and its reliability, plus the surrounding regulatory and legal framework. This change is also clear in aviation (e.g., drone operations), where moving from supervised to fully unmanned systems requires entirely new legal, infrastructure, and technology setups.

Another clear pattern is that autonomy is first introduced in controlled, lower-risk segments across transport sectors, and only later moves into more complex or dangerous areas. This segmentation allows stakeholders to build trust, refine technology, and collect real-world data before scaling to more complex applications. In road transport, driverless systems are fully tested in controlled environments such as dedicated test zones, private tracks, and simulators. Then they are deployed on predictable routes, such as highways with low pedestrian traffic, and only later in urban areas. Rail transport shows a similar trend. It starts with trials in a fixed track environment and the move to autonomous freight trains and metro lines in controlled settings, then moves on to mainline passenger services.

One key difference for maritime autonomy is the vast diversity in vessel types, sizes, and operating profiles. Unlike sectors such as aviation, rail, or even road transport, where vehicle platforms are relatively standardized, the global maritime fleet spans everything from small inland barges to massive trans-ocean ships. This diversity means that, while core autonomy systems can often be reused, their integration, calibration, and validation must be tailored to each vessel class and use case. MASS must prove reliability in a wide range of real-world conditions, vessel sizes, and use cases.

5.4. Contribution to the Literature

This study contributes to current literature by identifying and analyzing a combination of factors that have not yet been examined in relation to the different degrees of autonomy as stated by the IMO. It provides a structured, comparative analysis of the importance of adoption factors across IMO's DOA 2–4, helping to identify what influences the different DOAs. Our results show that there is a difference in the importance of factors across the different DOA.

In previous studies using the BWM [12, 13] experts were asked to rank factors influencing the adoption or commercialization of autonomous vessels in general, and only afterward were distinctions made between different degrees of autonomy. In contrast, this thesis required experts to evaluate and rank the importance of each factor separately for each DOA, allowing for a more precise understanding of how strategic priorities shift as autonomy increases. This approach addresses a key gap in the literature by showing that financial, technological, legal, and operational concerns are different between autonomy levels.

Furthermore, the findings indicate that the removal of human operators from vessels leads stakeholders to prioritize technological reliability and system maturity. This shift makes trust and perceived risk critical determinants of adoption of autonomous systems, requiring existing adoption models to be extended to explicitly integrate these factors.

Finally, it provides unique insights and concerns from experts on the adoption of different degrees of autonomy, different routes, and types of vessels that are more suitable for early adoption. Regarding different vessel types and routes, our findings support previous literature on the segments that will early adopt autonomous vessels.

5.5. Limitations and Future Research

While this study provides novel insights into the evolving importance of adoption factors across different degrees of maritime autonomy, some limitations must be acknowledged.

The sample size of 14 validated BWM responses, while sufficient for exploratory multi-criteria decision-making (MCDM), limits the generalizability of the results. Additionally, most respondents experience is in trans-ocean shipping, which may have influenced the factor prioritization. Future research can involve professionals with more varied backgrounds and can also include other types of vessels. Offshore support vessels, passenger ferries, and inland barges may present unique adoption dynamics due to differences in regulatory exposure, maintenance needs, and crew redundancy.

Another consideration is the presence of strong opinions on certain factors that may have disproportionately influenced the average results. It is important to determine if these strong views are consistent with a different pool of respondents. Future research should include a larger and more diverse sample to confirm whether these opinions persist.

Although the Best-Worst Method is well regarded for reducing comparison fatigue and improving consistency, its application in this study came with a challenge. The requirement to complete three separate BWM rankings may have led to reduced engagement, especially among senior professionals with limited time.

A significant divide exists among respondents about whether adoption factors differ by vessel type and route. While more than half of management-level participants acknowledged that prioritization would change depending on the route or vessel type, only one of non-management respondents agreed. Future studies could investigate this difference in views to understand how people's roles and experiences

influence their attitudes toward MASS adoption.

It is also worth noting that some respondents did not differentiate between the factors, possibly reflecting a belief that all core concerns are equally important during the transition to autonomy. Alternatively, this pattern may suggest skepticism about the feasibility of autonomous shipping. Future research should look into whether these uniform responses are due to confusion about the concepts or cautious attitudes toward change.

Furthermore, future studies could explore which ship types or routes still require a minimum level of onboard crew due to technical maintenance, cargo handling, or emergency preparedness requirements. Additionally, there is also a need to examine autonomy adoption not just by level (DOA 2–4), but by specific use cases and deployment timelines. A comparative timeline analysis could identify which vessel segments are likely to reach operational autonomy earliest and under what regulatory or technological conditions.

Another important research area is operations in mixed traffic environments, where autonomous, remotely operated, and conventional manned vessels share the same waterways. The future of the maritime environment will be a combination of autonomous and human-operated vessels around the world. Setting the right foundations for future seafarers is paramount to support the sector's evolution.

Finally, future extensive research focusing on cost-benefit analysis especially for DOA 2 vessels is crucial. Although this study focuses on the relative importance of adoption drivers, breaking down the economic factors into their key components could offer deeper insight into the trade-offs between initial investment, operational savings, and risk exposure.

6

Conclusion

This thesis has investigated the factors that guide the adoption of autonomous vessels from the perspective of shipowners, using insights from industry experts and a structured Multi-Criteria Decision-Making (MCDM) analysis. In addition, it identified the shipping segments most likely to emerge as early adopters. The main research question this thesis aimed to answer is:

What drives the adoption of autonomous cargo vessels by shipping companies, and in which segments are they likely to be introduced?

Specifically, the Best-Worst Method (BWM) was applied to determine the relative importance of nine key factors influencing adoption decisions across three different degrees of autonomy (DOA 2, DOA 3, DOA 4). The key results of the analysis are summarized below.

At DOA 2, the most significant considerations for shipowners are financial: "Investment, Development & Operational Costs" and "Economic & Business Advantages" are primary factors influencing adoption decisions. At this stage, human oversight serves as a safety net, allowing companies to evaluate the economic benefits of autonomy, as onboard crews can still manage and resolve technical issues.

As autonomy advances and onboard crews are removed (DOA 3 and DOA 4), the critical factor shifts toward "Vessel's Technological Maturity and Reliability," reflecting the industry's growing need for proven systems in uncrewed operations. Without humans onboard, decision-making moves from economic considerations to ensuring trust in technology and managing new risks, making pilot projects essential before wider adoption. Additionally, the increasing significance of the "Regulatory and Legal Framework" at higher autonomy levels emphasizes the crucial role of clear international rules and liability frameworks in enabling broader adoption. Continuous attention to "Emergency Response Capability" further highlights the industry's enduring commitment to safety as autonomy levels rise.

Overall, coastal and inland trades, and vessels such as containerships and Ro-Ro carriers, offer the most predictable environments for early trials. DOA 2 is identified as the most immediate feasible adoption stage, underscoring a preference for initial implementations that ensure operational safety, reliability, and effective financial risk management. Importantly, success at DOA 2 does not automatically lead to DOA 3 or DOA 4. Each autonomy level demands its own proof. The adoption of MASS may vary by route and vessel type.

A key insight from this research is that the relative importance of adoption factors shifts substantially between crewed and fully crewless operations. Our analysis revealed the importance of separately studying distinct degrees of autonomy rather than examining autonomous vessels as a general category. By recognizing the different degrees of autonomy as separate pathways rather than sequential phases, shipowners and stakeholders can better focus their investments, regulatory efforts, and trust-building strategies. This approach supports a future where higher levels of autonomy are both safe and economically feasible.

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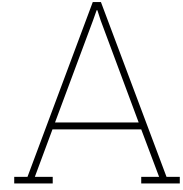
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Appendices



DOA 2 Respondents Tables

A.1. Best Factor & Best-to-Others Table

Res	Best	F1	F2	F3	F4	F5	F6	F7	F8	F9
1	F1	1	5	5	5	2	9	4	3	2
2	F2	9	1	5	7	1	9	9	7	7
3	F2	7	1	9	7	2	4	3	3	9
4	F1	1	5	9	8	5	7	6	5	2
5	F7	7	7	5	4	9	5	1	1	5
6	F2	3	1	3	3	4	7	3	4	3
7	F4	5	5	4	1	1	2	2	7	4
8	F1	1	1	3	3	4	7	3	1	2
9	F1	1	3	1	6	7	4	5	6	8
10	F9	3	3	9	2	8	1	4	4	1
11	F4	1	3	9	1	7	3	5	5	3
12	F7	1	1	1	1	1	1	1	9	3
13	F1	1	2	2	2	3	5	2	3	2
14	F7	9	7	5	3	2	3	1	2	6

F1: Economic and business advantage, F2: Investment, development and operational costs, F3: Insurance & premiums, F4: Vessel's technological maturity and reliability, F5: Port infrastructure readiness, F6: Standardization, F7: Emergency response capability, F8: Human-capital readiness, F9: Regulatory & legal framework.

A.2. Worst Factor & Others-to-Worst Table

Res	Worst	F1	F2	F3	F4	F5	F6	F7	F8	F9
1	F6	9	9	5	5	2	1	6	7	8
2	F6	9	9	5	5	1	1	7	6	5
3	F9	2	9	2	3	3	3	4	3	1
4	F3	9	4	1	3	5	4	4	5	7
5	F5	3	3	6	5	1	5	9	7	6
6	F6	5	7	4	5	4	1	4	3	4
7	F8	4	4	4	4	3	3	4	1	4
8	F6	7	6	5	4	3	1	5	6	5
9	F9	8	5	6	3	2	3	8	8	1
10	F3	7	7	1	8	2	9	5	5	9
11	F3	9	5	3	9	7	5	5	7	5
12	F3	3	5	1	9	5	5	1	9	5
13	F6	5	5	5	5	4	1	5	4	5
14	F6	3	3	2	5	5	1	3	4	5

F1: Economic and business advantage, F2: Investment, development and operational costs, F3: Insurance & premiums, F4: Vessel's technological maturity and reliability, F5: Port infrastructure readiness, F6: Standardization, F7: Emergency response capability, F8: Human-capital readiness, F9: Regulatory & legal framework.

B

DOA 3 Respondents Tables

B.1. Best-to-Others Table

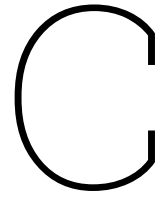
Res	Best	F1	F2	F3	F4	F5	F6	F7	F8	F9
1	F4	7	5	8	1	9	9	2	5	3
2	F8	1	5	5	1	3	9	9	1	1
3	F9	4	5	7	7	7	4	3	3	1
4	F4	4	3	8	1	7	7	7	9	3
5	F4	3	4	1	1	5	3	1	1	3
6	F4	3	3	4	1	4	5	4	3	3
7	F7	5	5	4	1	1	1	1	5	2
8	F4	2	2	2	1	3	9	1	2	1
9	F7	7	3	5	3	8	6	1	5	3
10	F8	3	3	7	2	7	1	4	1	3
11	F4	1	1	3	1	9	5	9	7	6
12	F4	1	1	1	1	5	5	9	9	5
13	F1	1	2	2	2	3	5	2	3	2
14	F7	1	2	3	3	5	3	1	3	2

F1: Economic and business advantage, F2: Investment, development and operational costs, F3: Insurance & premiums, F4: Vessel's technological maturity and reliability, F5: Port infrastructure readiness, F6: Standardization, F7: Emergency response capability, F8: Human-capital readiness, F9: Regulatory & legal framework.

B.2. Others-to-Worst Table

Res	Worst	F1	F2	F3	F4	F5	F6	F7	F8	F9
1	F6	7	8	8	9	9	1	8	5	9
2	F5	1	5	3	5	1	7	5	3	1
3	F6	4	4	4	5	4	2	6	4	4
4	F8	5	7	2	9	3	3	3	1	7
5	F9	5	3	1	3	1	3	7	8	1
6	F6	4	4	3	5	3	1	3	3	3
7	F1	1	1	2	8	8	5	5	1	2
8	F6	8	8	8	9	7	1	8	7	8
9	F1	3	5	6	5	5	6	7	5	2
10	F3	6	6	1	8	5	9	6	7	6
11	F6	9	9	5	5	9	1	9	6	5
12	F3	1	3	1	1	5	5	9	9	5
13	F6	5	5	5	5	4	1	5	4	5
14	F8	3	3	4	3	4	9	3	1	5

F1: Economic and business advantage, F2: Investment, development and operational costs, F3: Insurance & premiums, F4: Vessel's technological maturity and reliability, F5: Port infrastructure readiness, F6: Standardization, F7: Emergency response capability, F8: Human-capital readiness, F9: Regulatory & legal framework.



DOA 4 Respondents Tables

C.1. Best-to-Others Table

Res	Best	F1	F2	F3	F4	F5	F6	F7	F8	F9
1	F9	8	8	8	9	9	9	9	1	1
2	F5	1	1	1	1	1	1	1	7	1
3	F9	5	6	6	5	8	6	5	8	1
4	F4	5	6	8	1	8	8	7	9	5
5	F3	3	3	1	3	8	3	1	1	1
6	F4	3	3	3	1	5	5	3	3	3
7	F7	8	8	8	1	2	2	1	8	8
8	F4	2	2	2	1	3	8	1	2	1
9	F8	4	6	8	5	7	6	4	1	5
10	F9	3	3	8	3	5	2	4	1	1
12	F4	1	3	1	1	5	5	9	9	5
13	F1	1	2	2	2	2	5	2	4	2
14	F7	3	3	3	1	7	9	1	5	4

F1: Economic and business advantage, F2: Investment, development and operational costs, F3: Insurance & premiums, F4: Vessel's technological maturity and reliability, F5: Port infrastructure readiness, F6: Standardization, F7: Emergency response capability, F8: Human-capital readiness, F9: Regulatory & legal framework.

C.2. Others-to-Worst Table

Res	Worst	F1	F2	F3	F4	F5	F6	F7	F8	F9
1	F6	8	8	8	9	9	1	9	1	9
2	F3	7	9	7	7	7	5	5	7	1
3	F8	6	6	6	6	5	5	5	2	8
4	F8	4	3	2	9	2	2	3	1	7
5	F2	3	1	3	5	2	3	7	7	9
6	F6	4	4	3	5	3	1	3	3	3
7	F8	2	2	2	8	8	8	8	1	2
8	F6	8	8	8	8	7	1	9	8	9
9	F6	3	6	6	4	7	5	3	6	5
10	F2	6	6	1	7	4	9	7	9	3
12	F3	3	3	1	1	5	5	9	9	5
13	F6	5	5	5	5	5	1	5	3	5
14	F6	3	4	4	2	8	1	6	6	7

F1: Economic and business advantage, F2: Investment, development and operational costs, F3: Insurance & premiums, F4: Vessel's technological maturity and reliability, F5: Port infrastructure readiness, F6: Standardization, F7: Emergency response capability, F8: Human-capital readiness, F9: Regulatory & legal framework.

D

Survey Questionnaire

Adoption of Autonomous Vessels

Dear responder, we appreciate your acceptance to take part in the study. The overall purpose of this questionnaire is to determine the important factors that affect decision making of adopting autonomous vessels.

Initial information and consent

Your participation is greatly appreciated.

You are being invited to participate in a study titled "Navigating Autonomy: Factors affecting adoption of autonomous vessels". The study is conducted by Vasileios Delis from the TU Delft and the Technology, Management and Policy Department.

Autonomous ships can transform maritime transport by reducing human error, lowering costs, and decreasing pollution. Yet, adoption is slowed by high expenses, unclear rules, safety and cyber risks, and limited collaboration among industry players. This study identifies key factors that drive the shift toward autonomous vessels, from partially autonomous ships (remote support) to fully self-operating ones.

The survey will take about 10 minutes to complete.

As with any online activity, the risk of a breach is always possible. To the best of our ability your answers in this study will remain confidential. We will minimize any risks by storing the data in a secured TU Delft drive, accessible only by the TU Delft research team. Only anonymized and aggregated data will be described in publications. The data may be reused for future scientific and educational activities on the topic of adoption of autonomous vessels.

Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any questions.

By continuing with the survey, you acknowledge that you have been sufficiently informed about the study and consent to participate.

If you have any questions or comments, you can contact Vasileios Delis at v.delis@student.tudelt.nl.

By Selecting "Yes", you consent to the use of your responses in an anonymized and aggregated format.

- ☐ Yes
☐ No

Your Information

What is your company's name?

What is your current role in the company?

Is this a managerial role?

- ☐ Yes
☐ No

How many years of experience do you have in the maritime sector?

What kind of vessels do you have experience with?

Multiple selections are allowed.

- ☐ Bulk Carriers
☐ Containerships
☐ Tankers
☐ General Cargo Vessels
☐ Ro-Ro Vessels

What kind of routes do you have experience with?

Multiple selections are allowed.

- ☐ Trans-ocean
☐ Coastal (Short-sea)
☐ Inland

A small introduction about Autonomous Vessels

Maritime Autonomous Surface Ships (MASS) refer to vessels that can operate with varying degrees of automation, from remotely controlled ships with seafarers on standby, to fully autonomous ships requiring minimal or no direct human intervention. These technologies aim to improve efficiency, enhance safety by reducing human error, and open new business opportunities. The International Maritime Organizations classifies MASS into four levels of autonomy:

1. Degree One: Ship with automated processes and decision support. Seafarers onboard operate, supervise, and can take control when needed.
2. Degree Two: Remotely controlled ships with seafarers onboard that can take over when necessary.
3. Degree Three: Remotely controlled ships without crew onboard, operated entirely from a remote control center.
4. Degree Four: Fully autonomous ships capable of making and executing decisions without human intervention.

Key Factors and their explanations

- **Economic and business advantages:** Advantages related with improvements in profitability, new business opportunities, fuel efficiency, scheduling reliability and cost savings.
- **Investment, development and operational costs:** Initial investments for the development and adoption of MASS, retrofit/build costs, training and ongoing operational costs.
- **Insurance & premiums:** Availability of insuring ships against operational risks and potential liabilities, and risk-sharing models tailored to MASS operations.
- **Vessel's technological maturity and reliability:** Availability of mature technologies and systems that are reliable and resilient. I.e. navigation and anti-collision, communication and cyber and physical security systems. Ease of use of human-machine interfaces on vessels and shore-control centers.

- **Port infrastructure readiness:** Availability of smart-port features (automated berths, digital shore-control centers) plus port-side security measures (secure data links, access controls, anti-tamper systems).
- **Standardization:** Well-defined technical standards (e.g. data formats, control interfaces) reduce integration risk.
- **Emergency response capability:** Protocols and systems for collision, grounding, or system-failure scenarios of vessels.
- **Human-Capital Readiness:** Availability of training programs and skilled personnel for MASS operations (shore-crew upskilling, certifications, cross-disciplinary expertise).
- **Regulatory and legal framework:** Clarity and completeness of International Maritime Organization and flag-state rules (e.g. SOLAS, COLREGS, MARPOL) for unmanned operation including who is legally responsible if an accident happens.

Next, you will be asked to rank these factors for the different levels of autonomy: Levels 2, 3, and 4.

Degree of Autonomy 2 - Remote controlled vessels with onboard crew

Most & Least Important Factor

Click the icon next to each option to view more information.

- Which factor do you consider the **Least** important overall?

Click the icon next to each option to view more information.

- ### Comparing Most & Least important factors with the remaining factors

Where 1 = equal important and 9 = absolutely more important.

Click the icon next to each option to view more information.

[illegible]

	1 = Equal important	2	3 = Moderately more important	4	5 = Strongly more important	6	7 = Very strongly more important	8	9 = Absolutely more important
» Emergency response capability ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐
» Human-capital readiness ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐
» Regulatory & legal framework ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐

You identified **{q://QID119/ChoiceGroup/SelectedChoices}** as the **least** important factor.

Indicate how much **more important** are **the remaining criteria** compared to **{q://QID119/ChoiceGroup/SelectedChoices}**.

Where **1 = equal important** and **9 = absolutely more important**.

Click the ⓘ icon next to each option to view more information.

	1 = Equal important	2	3 = Moderately more important	4	5 = Strongly more important	6	7 = Very strongly more important	8	9 = Absolutely more important
» Economic and business advantage ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐
» Investment, development and operational costs ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐

	1 = Equal important	2	3 = Moderately more important	4	5 = Strongly more important	6	7 = Very strongly more important	8	9 = Absolutely more important
» Insurance & premiums ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐
» Vessel's technological maturity and reliability ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐
» Port infrastructure readiness ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐
» Standardization ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐
» Emergency response capability ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐
» Human-capital readiness ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐
» Regulatory & legal framework ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐

Degree of Autonomy 3 - Remote controlled vessels without onboard crew

Most & Least Important Factor

Click the  icon next to each option to view more information.

- Which factor do you consider the **Least** important overall?

Click the icon next to each option to view more information.

- ### Comparing Most & Least important factors with the remaining factors

Where 1 = equal important and 9 = absolutely more important.

Click the icon next to each option to view more information.

[illegible]

	1 = Equal important	2	3 = Moderately more important	4	5 = Strongly more important	6	7 = Very strongly more important	8	9 = Absolutely more important
» Emergency response capability ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐
» Human-capital readiness ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐
» Regulatory & legal framework ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐

You identified **{q://QID137/ChoiceGroup/SelectedChoices}** as the **least** important factor.

Indicate how much **more important** are **the remaining criteria** compared to **{q://QID137/ChoiceGroup/SelectedChoices}**.

Where **1 = equal important** and **9 = absolutely more important**.

Click the ⓘ icon next to each option to view more information.

	1 = Equal important	2	3 = Moderately more important	4	5 = Strongly more important	6	7 = Very strongly more important	8	9 = Absolutely more important
» Economic and business advantage ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐
» Investment, development and operational costs ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐

	1 = Equal important	2	3 = Moderately more important	4	5 = Strongly more important	6	7 = Very strongly more important	8	9 = Absolutely more important
» Insurance & premiums ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐
» Vessel's technological maturity and reliability ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐
» Port infrastructure readiness ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐
» Standardization ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐
» Emergency response capability ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐
» Human-capital readiness ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐
» Regulatory & legal framework ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐

Degree of Autonomy 4 - Fully autonomous vessels

Most & Least Important Factor

Click the icon next to each option to view more information.

- Which factor do you consider the **Least** important overall?

Click the  icon next to each option to view more information.

- ### Comparing Most & Least important factors with the remaining factors

Indicate how much **more important** is
 \$ {q://QID131/ChoiceGroup/SelectedChoices} **over each of the remaining 8 criteria.**

Where 1 = equal important and 9 = absolutely more important.

Click the icon next to each option to view more information.

[illegible]

	1 = Equal important	2	3 = Moderately more important	4	5 = Strongly more important	6	7 = Very strongly more important	8	9 = Absolutely more important
» Emergency response capability ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐
» Human-capital readiness ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐
» Regulatory & legal framework ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐

You identified **$\{q://QID132/ChoiceGroup/SelectedChoices\}$** as the least important factor.

Indicate how much **more important** are **the remaining criteria** compared to the **$\{q://QID132/ChoiceGroup/SelectedChoices\}$** .

Where **1 = equal important** and **9 = absolutely more important**.

Click the ⓘ icon next to each option to view more information.

	1 = Equal important	2	3 = Moderately more important	4	5 = Strongly more important	6	7 = Very strongly more important	8	9 = Absolutely more important
» Economic and business advantage ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐
» Investment, development and operational costs ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐

	1 = Equal important	2	3 = Moderately more important	4	5 = Strongly more important	6	7 = Very strongly more important	8	9 = Absolutely more important
» Insurance & premiums ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐
» Vessel's technological maturity and reliability ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐
» Port infrastructure readiness ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐
» Standardization ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐
» Emergency response capability ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐
» Human-capital readiness ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐
» Regulatory & legal framework ⓘ	☐	☐	☐	☐	☐	☐	☐	☐	☐

Different Types of Vessels and Various Sailing Scenarios

Which autonomy level do you consider most feasible for operational deployment by your company?

- ☐ Degree of Autonomy 2 – Remote controlled vessels with crew onboard
- ☐ Degree of Autonomy 3 – Remote controlled vessels without crew onboard
- ☐ Degree of Autonomy 4 – Fully autonomous vessel

Which types of routes are most likely to see early adoption of autonomous vessels in the industry?

Drag and drop the options to rank them in your preferred order.

Coastal (Short-sea)

Inland

Trans-ocean

Which vessel types are most likely to adopt autonomous technologies first in the commercial maritime industry?

Drag and drop the options to rank them in your preferred order.

Bulk Carriers

Containerships

Tankers

General Cargo Vessels

Ro-Ro Vessels

Do you think your previous responses about the importance of factors would change depending on the route or type of vessel?

- ☐ Yes
- ☐ No

If Yes, please explain below.

How likely is it that your company would adopt a vessel at the level you considered to be most feasible?

Not likely
☐

Likely
☐

Not sure
☐

Please explain which level of autonomy would your company be more likely to adopt and why?

Do you have any additional comments or suggestions about adopting autonomous vessels?

(Optional. Your feedback is welcome.)