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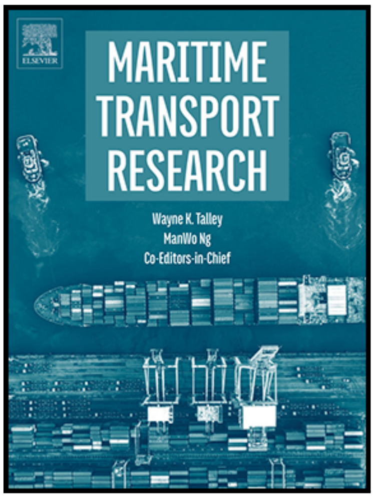

Economics of autonomous ships: from systematic review to guidelines for economic assessments

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Highlights

- 23 studies on economic assessment of autonomous ships identified within SLR
- The market and operational contexts, methodology and cost assumptions are analysed
- Findings reveal a highly heterogeneous research field
- Shortcomings: scarce data, uncritical reliance on sec. references, non-transparency
- Proposal of guidelines for standardized economic assessments of autonomous ships

Economics of autonomous ships: from systematic review to guidelines for economic assessments

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Jakob Lass-Ovens: Writing – original draft, Writing – review & editing, Methodology, Data curation, Conceptualization, Formal Analysis. **Håvard Nordahl**: Writing – original draft, Writing – review & editing, Formal Analysis, Validation, Methodology, Conceptualization. **Patrick Specht**: Writing – original draft, Writing – review & editing, Validation, Methodology, Conceptualization. **Lars Andreas Lien Wennersberg**: Writing – review & editing, Validation.

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Declaration of generative AI use

During the preparation of this work the authors used OpenAI GPT5.2 and Mistral-Small-3.2-24B in order to refine sentence structures. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

The authors declare to not have any known financial or personal relationships with other people or organizations that could inappropriately have influenced or biased this work.

Economics of autonomous ships: from systematic review to guidelines for economic assessments

Abstract: The economic performance of autonomous ships is considered to be one of the key determinants for larger-scale commercial uptake. It is therefore not surprising that a growing number of researchers and industry-driven initiatives aim to provide investment and cost estimates. However, the extent to which these assessments are comparable, transparent and methodologically sound remains unclear. Based on a structured review of 23 studies, this paper systematically examines and synthesizes the existing body of economic analyses on autonomous cargo ships. The study identifies the markets, operational contexts, methodological approaches and key assumptions that affect cost estimates. The findings reveal a highly heterogeneous research field in which scenarios and autonomy concepts, methodological approaches and reported results vary considerably. Empirical cost data and original cost estimates remain scarce, leading some studies to rely significantly on secondary sources, which are sometimes adopted without critical evaluation. As a result, misunderstandings or optimistic biases risk being propagated through the literature. Furthermore, a lack of transparent assumptions or ambiguous documentation makes it difficult to understand, assess and reproduce individual results. Taken together, these issues ultimately limit the practical value of scientific economic assessments of autonomous cargo ships. To address this issue, the paper proposes transparency guidelines that researchers and reviewers can use to ensure assumptions and decisions are disclosed in a manner that allows for systematic interpretation and comparison across economic assessments. In this way, the framework contributes to more robust knowledge development and better-informed decision-making regarding the economics of autonomous shipping.

Keywords: autonomous shipping, economic assessment, cost estimation, systematic review, methodological transparency, maritime economics

1 Introduction

Autonomous shipping is associated with a range of societal, environmental, and economic benefits. Frequently claimed expectations include addressing recruitment challenges, improving operational safety, reducing emissions, fostering a modal shift from road to waterborne transport, increasing cargo capacity, and improving economic performance (Kurt and Aymelek, 2022; Munim, 2019; Nordahl et al., 2023; Rødseth, 2018). Since financial considerations typically dominate investment decisions in the shipping industry (Fonseca et al., 2021; Munim et al., 2025), it is reasonable to assume that anticipated economic performance is the primary driver for commercial deployment of autonomous ships.

Advances in autonomous shipping technologies can be observed in research and industry pilot projects (Kongsberg Maritime, 2023; Nippon Foundation, 2024; NTNU, 2026; Prevljak, 2024; Websteks and Rychaon, 2025) as well as investments by commercial actors in remotely controlled and autonomous ships (Kongsberg Maritime, 2020; Ocean Infinity, 2022; Parker, 2025; Seafar, 2022; Yara, 2024). As of today, however, the only commercial cargo ships purposely built for uncrewed autonomous operations are the Yara Birkeland (Yara, 2024) and the ASKO ships MS Marit and MS Therese (Kongsberg Maritime, 2020). An uncrewed ship in the context of this study means a cargo ship without any persons onboard during the voyage (ISO, 2022). The decision to build and operate the uncrewed ASKO ships was taken in 2020, and no similar announcements have been made since then. This suggests that potential investors remain unconvinced by the claimed benefits, indicating that the investment risk is perceived as too high. In contrast, the market for unmanned surface vessels (USV) shows stronger momentum, with actors like Reach Subsea investing in large USVs to replace offshore service vessels (Håvardsholm, 2025a, 2025b). While the underlying technology might be the same for USVs and autonomous ships, the risk profiles and approval processes are not. This is due to the smaller size of USVs, being boats, making them subject to different rules and regulations. Furthermore, since USVs like the "Reach Remote 1" replace ships several times larger, the associated cost savings are considerably higher than those achievable for merchant ships. This implies significantly lower investment risk.

To reduce investment risk and stimulate adoption of autonomous shipping, there are at least five constraining factors that must be overcome (Malmquist and Munim, 2025; Nordahl et al., 2023). These include immature or absent regulations and standards for autonomous ships (Ahmed et al., 2024; Jin and Lee, 2024; Orzechowski et al., 2024), making approval processes costly and time consuming. Current technological limitations further restrict autonomy to operational modes that require high involvement of remote operators (Kim and Schröder-Hinrichs, 2021; Nordahl et al., 2023; Wennersberg et al., 2026). This, at least temporarily, reduces the cost saving potential by constraining multi-ship operations from remote operating centres (ROC). Furthermore, a lack of supporting infrastructure and port services imply that investments are needed (Malmquist and Munim, 2025; Wennersberg et al., 2026), and increased time spent in ports (e.g., for maintenance) may reduce productivity (Kurt and Aymelek, 2022). Finally, immature or missing business models (Ayuso et al., 2025; Nordahl et al., 2023), are additional factors that together yield economic uncertainty and investment risk for uncrewed autonomous ships.

Scientific research has the potential to support or challenge claims regarding the economic prospects of autonomous shipping and, in doing so, reduce uncertainty in commercial decision-making (Munim et al., 2025; Negenborn et al., 2023). It is therefore not surprising that several researchers have approached this problem (Ziajka-Poznańska and Montewka, 2021). However, the inherent characteristics of autonomous shipping impose demanding requirements for credible economic assessments: First, conceptual understandings of autonomous shipping, including the associated operational, logistical and business concepts, vary considerably across practitioners, legislators and scholars. If the studied autonomous ship concept is not explicitly defined, ambiguity may arise in the interpretation of results, thereby limiting the scientific value of the contribution. Second, low technological readiness and market maturity mean that empirical data on cost structures and operational performance are scarce or unavailable. Consequently, economic assessments on autonomous ships are necessarily driven by assumptions (Ghaderi, 2020; Ziajka-Poznańska and Montewka, 2021). This may result in highly sensitive models in which minor methodological choices or variations in assumptions can lead to substantial differences in outcomes. Insufficient transparency in documenting these choices may mask the speculative nature of results and create an impression of unwarranted precision. To maintain scientific credibility, and epistemological robustness and practical relevance for commercial decision-making, economic assessments on autonomous ship operations must therefore adhere to high standards of methodological rigor and transparency.

This paper examines and integrates the existing body of economic assessments for autonomous cargo ship operations. In this paper, the term "economic" or "financial" analysis refers to firm-level economic assessments focusing on costs, revenues, and evaluation methods, rather than macro-economic impact assessments. Adding to that, the use of the term "ship" is not limited to specific vessel types and includes deep-sea and short-sea ships as well as inland vessels. Using a systematic review approach, relevant scientific contributions are incorporated into the analysis. The objective in this paper is to provide a clearer understanding of the established knowledge, the methods, assumptions that are used when assessing economics of autonomous ships. This is done by identifying common approaches, methodological gaps as well as inconsistencies. This work herein extends and updates existing reviews such as Ziajka-Poznańska and Montewka (2021). They found that valid economic or financial models of autonomous shipping are lacking, and that there is significant uncertainty affecting cost estimates. Building on these findings, this study thus addresses the methodological basis of existing economic assessments in greater detail with a focus on methods, assumptions and underlying cost estimations. The results show that there are several shortcomings in the literature that compromises comparability and reproducibility of results. Therefore, we propose guidelines for economic assessments for autonomous cargo ships intended to prevent these shortcomings in future assessments by improving transparency and ensuring reproducibility of results. This study is following three research questions:

- RQ1: In which markets and operational contexts does the literature study the implications of autonomous shipping concepts on the economics of ship operations?

- RQ2: In which way and by what methods are the costs of autonomous ship operation assessed?
- RQ3: How are key cost items estimated and how are they impacted by assumptions and uncertainties?

The remainder of this paper is structured as follows. Section 2 introduces the definition of autonomous shipping and the framework of ship economics, both of which are used in the analysis of literature. Section 3 presents the methodology applied to identify and screen literature, analyse papers and synthesise results. Section 4 presents the results of the analysis and answers the three research questions. Finally, results are synthesised and discussed in Section 5, leading to proposed guidelines. Section 6 concludes this work and provides an outlook for future work.

2 Background

2.1 Definition of abbreviations used in the paper

Abbreviation	Definition	Abbreviation	Definition
ACF	Annual cashflow	NPV	Net present value
AUV	Autonomous underwater vehicle	OA	Operator assisted
CA	Constrained autonomous	OPEX	Operating expenditures
CAPEX	Capital expenditures	RFR	Required freight rate
DCF	Discounted cash-flow	ROC	Remote operating centre
FA	Fully autonomous	RSE	Regulatory scoping exercise
IMO	International Maritime Organization	USV	Unmanned surface vessel
IRR	internal rate of return	VCF	Voyage cashflow
MASS	Maritime autonomous surface ship	VOYEX	Voyage expenditures

2.2 Working definition of autonomous shipping

In the context of this study, the definition of autonomous shipping is essential for delimiting the scope of the literature review, and for categorizing findings from the reviewed documents. The definition of a Maritime Autonomous Surface Ship (MASS), commonly referred to as an autonomous ship, has been discussed extensively in literature. It should be noted that the frequently cited International Maritime Organization (IMO) definitions and autonomy levels (IMO, 2018) were intended to be a basis for the regulatory scoping exercise (RSE). Early proposals for defining autonomy levels submitted to the IMO Maritime Safety Committee are discussed in Bratić et al. (2019), and autonomy levels proposed by classification societies are discussed in Bratić et al. (2019) and Fukuto (2021). The need for a more formal and quantifiable autonomy level definition is discussed in Rødseth et al. (2022a), leading to autonomy level proposals based on time constants defining how many minutes into the future automation can be safely in control without human supervision. This proposal was combined with the operational envelope concept and proposed as a method for approval of MASS in Rødseth et al. (2022b). Autonomy levels as a concept are criticized in Rødseth and Wennersberg (2023), and operational modes are proposed as a more suitable concept. The RSE concluded in May 2021 (IMO, 2021) and the IMO is currently developing a non-mandatory MASS code in which autonomy levels as a concept have been abandoned in favour of operational modes (IMO, 2024a). The International Organization for Standardization (ISO) has proposed a vocabulary related to autonomous ship systems (ISO, 2022), however, a final definition of MASS is likely not achieved until the non-mandatory MASS code, which at time of writing is expected to be adopted for voluntary use in 2026 (IMO, 2024b). While a final definition of MASS is pending, it can be observed from both literature, ISO and IMO, that MASS can be understood as a maritime surface ship that can, to some degree, operate independently of human supervision. As this is a rather open definition, additional specifications are needed, to limit the scope and simplify the document selection and analysis process. There are applications of autonomy in several areas, such as Autonomous Underwater Vehicles (AUVs), passenger transport, naval ships, and cargo ships.

This study restricts the analysis to merchant autonomous ships that are operated in maritime, inland, and coastal waters. That means, ships for passenger transport, AUVs, and naval ships are not included. This study also defines an autonomous ship as one where autonomy is used to either change the working environment of the crew, predominantly by moving them to a control centre, or to replace functions normally performed by the crew leading to reductions in their numbers, and/or to enable significant changes to the ship design, typically to remove the bridge. This is a bit stricter definition than “being able to operate independently of human interaction, to some degree”, as it excludes some applications of technology typically associated with autonomous ships. See Table 1 for further details on how autonomous ships are defined in this review.

Table 1: Scoping the review by the definition of autonomous ships.

In scope	Not in scope
Uncrewed cargo ships	Naval ships, and any ship not engaged in cargo freight (e.g., cruise and passenger, fishing, service and research ships).
Reduced crew cargo ships enabled by automation replacing functions normally performed by the crew	Any ship using auto-docking, auto-tracking, or other autonomous navigational equipment, but where the crew remains onboard and is not reduced in numbers, and where the technology is not used to realize a more efficient ship design.
Improved design in terms of cargo capacity and/or efficiency, enabled by autonomy	

Whether documents refer to concrete autonomy levels or operational modes or not, there are some differences in what economic impacts one would expect depending on the assumed autonomy level or operational mode, and what concept it has been used to realize. Taking the proposed autonomy levels in Rødseth et al. (2022a) as an example, the autonomy level “Remote Control” is said to enable uncrewed ships but depends on operators constantly monitoring and controlling the ship, whereas autonomy level “Constrained Autonomous” (CA) is said to enable periodically unattended operations. While remote control implies a one-to-one relation between the operator team in the ROC and the autonomous ship, CA could enable a one-to-many relation between the ROC operator team and several autonomous ships. This in turn implies lower ROC cost per autonomous ship for CA than for remote control. Table 2 gives the reader an overview of how operational mode and crewing level are understood within the scope of this review.

Table 2: Definition of operational mode, crewing level and ROC concept.

Category	Grouping variable	Definition used herein
Operational mode	OA – Operator Assisted	The autonomous ship is continuously monitored from an ROC in a one-to-one relationship between operators and the autonomous ship. The number of operators may vary as one could expect differences in assumed new roles to cover the functions navigator, chief and master. Both direct remote control and supervised automation or autonomy falls into this category.

Operational mode	CA – Constrained Autonomous	The autonomous ship is discontinuously monitored from an ROC in a one-to-many relationship between an operator team and a fleet of autonomous ship. The operator, or operators as discussed in the OA definition, monitor several autonomous ships and are only expected to actively engage in problem solving or taking control when the autonomous ship issues requests to intervene or alarms. Automation of all main functions, and some autonomous decision making is implied.
Operational mode	FA – Fully Autonomous	The autonomous ship can execute all operations without support from human operators. There would still be a ROC with operators, but their role would be related to mission planning and administrative tasks, as well as exception handling (e.g., recovery from fallback states). Automation of all main functions and autonomous decision making is implied.
Crewing level	Crewed	There is a human crew onboard and the number of crew is equivalent to conventional ships.
Crewing level	Reduced crew	There is a human crew onboard, but the number of crew is reduced compared to a similar conventional ship.
Crewing level	Uncrewed	There are no humans onboard during normal operations. Humans can enter the ship for specific tasks, such as maintenance and repairs.

2.3 Analytical framework for ship operating economics

The analyses of the economics of ship operation typically revolve around the understanding of the costs and revenues that are associated with the management of a ship. They typically take a shipowner's – or shipping company's – perspective. Usually, shipping companies operate not only one, but a fleet of ships. Furthermore, the operation of a ship always results in different cost categories. In the absence of an industry standard (Rojon et al., 2021), the five cost categories proposed by Stopford (2009) serve as an established framework in the shipping sector. The framework further specifies cost items attributed to each cost category. Given its widespread use, the framework is adopted by this paper to evaluate the consideration of costs in the existing literature on the economics of autonomous cargo ships.

First, operating costs (OPEX – operating expenditures), as proposed by Stopford (2009) refer to the daily operation of a ship and include costs for wages and provision of the crew, insurance of the ship, maintenance and repair of the ship, spare parts, registration fees and any other general costs. This category also includes the costs for administrative and commercial work or the rental of office spaces (Belesis et al., 2024; Drewry Maritime Research, 2018). In most cases, the largest driver of operating costs in conventional ships is considered to be crewing (Drewry Maritime Research, 2018). Regular dry dockings and special surveys are part of the second cost category: periodic maintenance costs. While these costs are considered as an individual item by Stopford (2009), some sources considered them as part of OPEX (Drewry Maritime Research, 2018). The third cost category is voyage expenditures (VOYEX) and are another potentially large category of costs in shipping. As opposed to OPEX, VOYEX only arise if a ship is actively involved in a trade. VOYEX are therefore being considered as variable costs, while OPEX are typically more or less fixed (Dantas and Theotokatos, 2023). By far the largest contributor toward VOYEX are expenditures for fuelling the ship. The share of fuel cost in VOYEX varies based on the fuel price and the market conditions (Notteboom and Vernimmen, 2009; Ronen, 2011). Besides fuel, further contributors to voyage costs can be port fees, canal dues, pilotage, towage and mooring. Cargo-handling costs make up the fourth cost category and include costs associated with the loading, discharging and stowage of cargo in port. Although typically borne by the charterer or cargo owner, these costs are an important contributor to the total cost structure of a ship, which holds especially true, when it is operated in a liner service (Stopford, 2009). Capital costs (CAPEX – capital expenditures) are the fifth cost category. They distinguish themselves from the other cost blocks as being asset-related costs, that are tied to ownership rather than to the actual operation of a ship (Stopford, 2009). The financing structure of a ship significantly affects CAPEX. In addition to the initial acquisition and eventual resale of the vessel, capital costs reflect the cost of both debt and equity financing. While debt financing incorporates interest payments and generates explicit cashflows, equity capital also represents an obligation since investors expect returns on their investment. Depending on the capital structure and financing terms, these components can result in substantial capital costs.

When carrying out financial assessments, methods can be distinguished according to whether the time value of money is explicitly considered. In the literature, a common distinction is made between non-discounted and discounted cash flow approaches (Berk and DeMarzo, 2024; Pšunder, 2012). Within this paper, we follow the differentiation of Poggensee and Poggensee (2021) and refer to these as “static” and “dynamic” respectively. Static approaches typically consider single periods or average values and ignore the time value of money. Dynamic analyses evaluate cashflows over multiple periods and discount them accordingly. While static approaches are well suited for short-term or operational decision-making, dynamic analyses typically bring greater explanatory power to investment decisions by explicitly incorporating the timing of costs and revenues (Poggensee and Poggensee, 2021). Static methods include one-period cost analyses and comparisons, or break-even calculations and amortisation calculations. Dynamic approaches comprise discounted cash-flow (DCF) techniques such as net present value (NPV) calculation, internal rate of return (IRR) or dynamic break-even analysis.

In the shipping industry, several derivatives of such methods are commonly applied. An example is the so-called voyage cashflow (VCF) analysis, which is commonly used in chartering to calculate the average daily earnings of a voyage (Heisenberg Shipping, 2024) and typically represents a static operational assessment. Annual cashflow (ACF) analysis is used to assess the economic performance of an individual ship or a fleet (Stopford, 2009) and may constitute either a static or a dynamic approach depending on whether discounting is applied. The required freight rate (RFR) analysis is an established way to determine the required minimum revenue that must be earned to generate profits (Stopford, 2009) and when based on discounted lifecycle cashflows corresponds to a net present value based break-even calculation.

3 Methodology

The research questions stated in Section 1 reflect the ambition of this study, which is to synthesize and systematically examine findings of and approaches to economic assessments of autonomous ship operations, and thus ultimately provide guidance for further advancement of the scientific toolset. In this endeavour, a systematic literature review approach is used. Compared to “traditional” or “scholastic” literature reviews which inherit a significant degree of subjectivity and randomness, systematic literature reviews are carried out in a structured way and thus allow for traceable and reproducible, as well as comprehensible, results (Cooper, 2010; Fink, 2005; Gough et al., 2017; Hart, 2018; Tranfield et al., 2003). Over the years, different frameworks for systematic literature review have emerged from various disciplines. An overview is given by Cardoso Ermel et al. (2021) that indicates that all approaches have a commonality by incorporating a “review”, an “analysis” and a “synthesis” stage which can be further broken down into specific steps and actions. The review stage incorporates the scope definition as well as the identification and screening of relevant literature, while the analysis is dedicated to extracting and describing essential components of the independent sources at hand. Lastly, the synthesis phase is used to interconnect the extracted components to generate new knowledge (Cardoso Ermel et al., 2021, pp. 22–24). For the documentation of the rationale, process and results of the systematic literature review, we have followed the PRISMA guidelines (Page et al., 2021) to ensure a high level of scientific rigor.

3.1 *Identification stage*

The data acquisition phase has been guided by a keyword-based search strategy which was applied to the Elsevier Scopus[1] database. The database has been chosen due to its multidisciplinary coverage of different scientific outlets, its focus on peer-reviewed literature and the indexing standards required to produce replicable results in literature reviews. Identified records were automatically indexed along with basic bibliometric data within the reference management software "Zotero"[2]. The initial search within the Scopus database, which was carried out in January 2026 using the keyword string referenced in Appendix A1 yielded a total of 1,876 records, from which 1,026 were removed by filtering languages, doctypes and keywords. Aside from sources found in the databases, the review may also include records that were retrieved within citation searches within eligible records, which is commonly referred to as "backward search" (Hirt et al., 2024). This step resulted in three additional studies from which one was evaluated eligible.

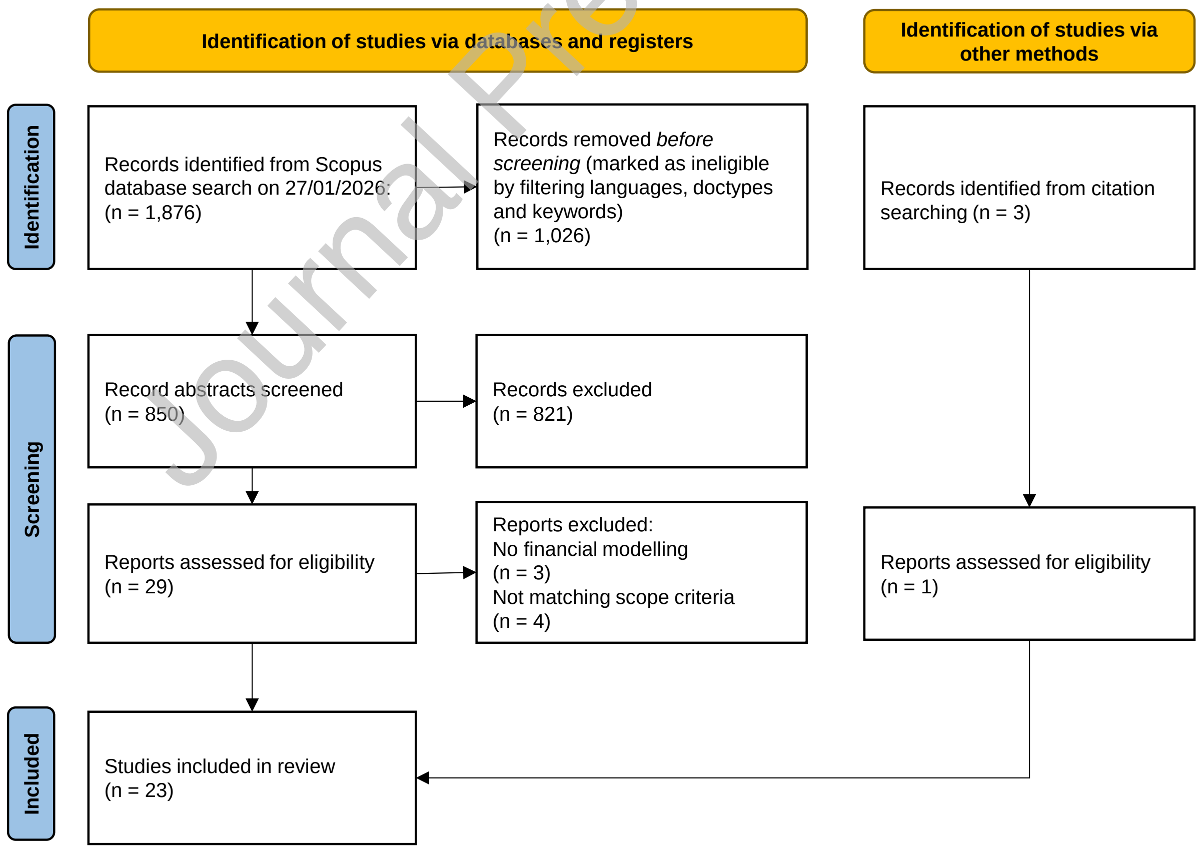
3.2 *Screening stage*

As part of the screening stage, a set of inclusion and exclusion criteria is defined in advance to guide the screening process and obtain a set of highly relevant articles and reports:

To be eligible for the review, articles must be written in English and adhere to common scientific standards. As such, only documents that are published in conference proceedings and peer-reviewed scientific journals are considered. No restrictions are made with regard to the date of publication.

The content of the articles must cover original work on financial modelling of autonomous cargo ship operations. Therefore, secondary studies, such as literature review papers or condensed versions of previous reports, are excluded from the analysis.

As part of an initial abstract screening, 821 studies were excluded due to failing these criteria. A further in-depth assessment of full texts resulted in the exclusion of another seven studies either due to



[1] https://www.scopus.com/

[2] https://www.zotero.org/

not incorporating financial modelling (n=3) or due to missing scope (n=4). The process and outcome of the identification and screening phases is illustrated in Fig. 1.

Fig. 1: Results of the literature identification and selection process based on (Page et al., 2021).

3.3 Analysis stage

The final panel consists of 23 studies that were published between 2017 and 2025 and includes twelve scientific journals and eleven conference papers. The studies that were included in the analysis are shown in the tables of Section 4.

An in-depth analysis of all records has been carried out by a team of three researchers with an academic background in the field of autonomous shipping as well as shipping economics. To ensure consistency, each study was reviewed independently by at least two researchers using a common evaluation scheme aimed at the coding of information across the studies and the reduction of individual interpretation. In cases of contradicting reviews a third review was conducted, and results of the individual reviews were aligned as an extraction to be used in the following synthesis.

The common evaluation scheme builds on the background provided in Sections 2.1 and 2.3. Aside from qualitative collection of information on the considered Autonomous ship concept, the scheme covers the underlying research design and methods used as well as the considered aspects of ship operation economics. The evaluation scheme for the panel is found in the Appendix A2.

3.4 Synthesis stage

The synthesis approach must be suitable for both the research questions and the nature of the primary studies under review. As these studies are heterogenous in design they need to be analysed by means of qualitative variables that represent complex constructs. Given the objective of mapping and structuring existing approaches in order to derive guidance and ultimately improve economic assessment practices for autonomous cargo ships, a statistical aggregation of findings is not appropriate and thus is not in scope of this work.

Accordingly, the synthesis stage follows a configurative approach, which emphasizes the identification, comparison, and conceptual organization of methodological approaches (Gough et al., 2017; Morandi and Camargo, 2015). Specifically, this involves grouping studies according to their underlying methodological characteristics, analysing key components and assumptions, and developing a structured categorization to systematize the range of approaches identified in the literature. The synthesis builds on the extracted information from the analysis stage.

4 Results

4.1 Markets and operational contexts

This section examines research question 1 by analysing the markets and operational contexts considered in the literature on the economics of autonomous ship operations. As can be observed from Table 3, the analysed papers refer to different operational and market contexts. The panel covers three distinct operational environments. Deep-sea shipping, defined as long-haul maritime transport between continents, was covered in four papers. Coastal or short-sea shipping, referring to transport between ports on the same continent or within a single country, often in coastal waters, was examined in eleven papers. Five papers discussed applications in inland waterway transport, concerning transport on rivers, canals, or lakes. Moreover, three studies focused on multiple operational settings rather than only one. Furthermore, it can be observed that autonomous ships are discussed to serve different transport markets. In the deep-sea shipping, the markets of container shipping, ConRo shipping, dry bulk shipping and liquid bulk shipping were addressed by one paper each. In coastal or short-sea shipping, eight contributions were related to container shipping, while dry bulk shipping, RoPax ferry services and aquaculture supply services were each represented by one paper. Within inland waterway transport, container shipping is also the most studied segment with two papers, while dry bulk and RoRo shipping each appear once, while one does not specify the transport market. All three publications that consider multiple operational environments take place within container shipping. Overall, the panel indicates a concentration of academic interest in container shipping across all operational environments.

Table 3: Number of papers by operational environment and transport market.

Operational environment	Transport market	#	Papers
Deep-sea shipping	Container shipping	1	(Jovanović et al., 2021)
	ConRo shipping	1	(Ammar, 2025)
	Dry Bulk shipping	1	(Kretschmann et al., 2017)
	Liquid bulk shipping	1	(Lee et al., 2021)
Coastal or short-sea shipping	Container shipping	8	(Akbar et al., 2021; Ghaderi, 2019; Gribkovskaia et al., 2019; Kooij et al., 2021; Nordahl et al., 2024, 2022; Santos and Guedes Soares, 2018; Tangstad et al., 2023)
	Dry bulk shipping	1	(Chaplin, 2019)
	RoPax ferry services	1	(Jovanović et al., 2022b)
	Aquaculture supply services	1	(Dantas and Theotokatos, 2023)
Inland waterway transport	Container shipping	2	(Alias and Felde, 2022; Wang et al., 2023)
	Dry bulk shipping	1	(Rosas and Verduijn, 2023)
	RoRo shipping	1	(S.P. Parvasi et al., 2025)
	Not specified	1	(Verberght and Van Hassel, 2019)
Various	Container shipping	3	(Jovanović et al., 2022a; Kooij, 2022; Seyed Parsa Parvasi et al., 2025)

Table 4 indicates that the reviewed papers address settings that are located across different geographical areas. This includes specific countries such as Australia, China, Norway and the United Kingdom, but also supranational regions such as the European Union. The latter emerges as a dominant region within the panel and is represented by three coastal or short-sea shipping papers as well as four inland waterway transport studies. Norway accounts for the largest number of six papers originating from a single country, which all involve coastal or short-sea shipping cases. Australia, China, the Middle East and the United Kingdom are represented by one contribution each. Three of the deep-sea contexts refer to various geographical settings as do three papers that cover various operational environments.

Table 4: Number of papers by geographical area and operational environment.

Geographical area	Operational environment	#	Papers
Australia	Coastal/Short-sea shipping	1	(Ghaderi, 2019)
China	Inland waterway transport	1	(Wang et al., 2023)
European Union	Coastal/Short-sea shipping	3	(Jovanović et al., 2022b; Kooij et al., 2021; Santos and Guedes Soares, 2018)

	Inland waterway transport	4	(Alias and Felde, 2022; S.P. Parvasi et al., 2025; Rosas and Verduijn, 2023; Verberght and Van Hassel, 2019)
Middle East	Deep-sea shipping	1	(Ammar, 2025)
Norway	Coastal/Short-sea shipping	6	(Akbar et al., 2021; Dantas and Theotokatos, 2023; Gribkovskaia et al., 2019; Nordahl et al., 2024, 2022; Tangstad et al., 2023)
United Kingdom	Coastal/Short-sea shipping	1	(Chaplin, 2019)
Various	Deep-sea shipping	3	(Jovanović et al., 2021; Kretschmann et al., 2017; Lee et al., 2021)
	Various	3	(Jovanović et al., 2022a; Kooij, 2022; Seyed Parsa Parvasi et al., 2025)

With regards to the autonomous shipping concepts considered within the reviewed papers all 23 studies assume a ROC operation of some kind. Notably, Gribkovskaia et al. (2019) assume that the control room is located onboard and below deck. Regarding the assumed operational mode and crewing level, more variations are observed. Apart from that, many studies do not explicitly define the autonomous shipping concept in terms of operational mode (or autonomy level). However, for some studies it is possible to deduce the operational mode. As an example for such a deduction, Rosas and Verduijn (2023) study three concepts M2-TO, M2-TOCR and M4-TOCR , where M2 and M4 denotes the ship type, TO that the ship is tele-operated, i.e., remotely controlled, and CR denotes crew reduction. This information leads to the assumption, that the operational mode is likely to be OA, CA and CA, respectively, for the three concepts. Since most of the studies do not explicitly state the operational mode, the information provided within each study was utilized in a similar way to deduce the operational mode - as defined in Table 2 - and the crewing level for the purpose of this review. The results are given in Table 5. For five of the reviewed publications, it is not possible to conclude on an assumed operational mode, which makes it hard to compare results of these studies with other studies. Of the remaining panel, 16 studies consider CA either directly or within the scope of a transition from conventional or OA towards CA. Fully autonomous operation is only considered within three publications. Once as a part of a transition period from CA and twice directly. These findings indicate that at the moment, constrained autonomy is commonly viewed as a necessity for economic viability, while full autonomy does not find that much consideration. The latter might be an indication that authors consider full autonomy to be unlikely to happen under the current circumstances.

Table 5: Number of papers by autonomous ship concept.

Operational mode	Crewing level	#	Papers
Conventional to CA in steps	Reduced crew to uncrewed in steps	1	(Kooij et al., 2021)
	Reduced crew	1	(Lee et al., 2021)
OA to CA in steps	Reduced crew	1	(Rosas and Verduijn, 2023)
CA	Uncrewed	10	(Chaplin, 2019; Dantas and Theotokatos, 2023; Ghaderi, 2019; Kretschmann et al., 2017; Nordahl et al., 2024; Seyed Parsa Parvasi et al., 2025; S.P. Parvasi et al., 2025; Santos and

			Guedes Soares, 2018; Tangstad et al., 2023; Verberght and Van Hassel, 2019)
	Reduced crew	2	(Gribkovskaia et al., 2019; Nordahl et al., 2022)
CA to FA	Reduced crew & uncrewed	1	(Alias and Felde, 2022)
FA	Uncrewed	2	(Akbar et al., 2021; Ammar, 2025)
Not clear/Mixed	Uncrewed	4	(Jovanović et al., 2022a, 2022b, 2021)
	Crewed and uncrewed	1	(Wang et al., 2023)

4.2 Methods for cost determination of autonomous ship operations

The analysis of approaches and methodologies, which aims to answer research question 2 aiming at the methods used to estimate costs of autonomous ships, reveals substantial variation in how real-world financial dynamics are addressed. Approaches are classified as "static" when the analysis is conducted for a single time period only and the time value of money therefore not considered. A period may be defined in different ways, for example as a month, a year or a rotation of a liner service. Approaches that cover multiple periods but do not discount future cashflows are classified as "semi-dynamic", whereas approaches that incorporate the time value of money over multiple periods are considered "dynamic". Table 6 shows that, within the panel, 13 studies follow a static approach, while seven are classified as dynamic. The remaining three studies make use of a semi-dynamic design. This distinction is relevant since ships typically require large investments and have a long operating life. Neglecting the timing of revenues and costs could severely distort the outcome and the value of economic assessments.

With respect to methodological implementation, all studies classified as dynamic employ discounted cashflow models, using the present values of different cashflow components to evaluate the investigated use case(s). Two of these dynamic studies additionally apply a break-even analysis. Studies of semi-dynamic nature predominantly focus on basic cost accounting and cost comparison. Only one semi-dynamic study conducts a break-even analysis in static form to compare conventional and autonomous use cases. In the case of static analyses, simple cost comparison is the predominant method, adopted by all of the static studies. The most common metrics in these studies are costs per transported unit (e.g., cost per ton or TEU) or costs per unit of time.

Across the reviewed panel and across all methodological approaches, 14 studies conduct sensitivity analyses of varying depth. Sensitivity analysis is used to make visible the reliability of the results and the uncertainty around individual cost items by changing key variables and determining the effect of these changes on the overall outcome. However, the scope and conduct of these analyses differ across studies.

With regards to the cashflow scope only four studies conduct a full investment appraisal and thus consider all main cost categories – CAPEX, OPEX and VOYEX – as well as any revenue related cashflows. The majority of the studies limit their economic assessments to costs only. While most of those still include the main cost categories to varying extents, four studies adopt a reduced cost scope that involves only selected cost categories or even individual cost items. For example, Ghaderi (2019) limits the economic evaluation exclusively to crew costs.

Table 6: Number of papers by approach and methodology used to assess cashflows.

Paper	Approach	Methods	Metrics	Cashflow scope	Sensitivity analysis
(Alias and Felde, 2022)	Static	Comparative cost analysis	Cost per TEU	Red.cost scope (OPEX + VOYEX)	No

(Chaplin, 2019)	Static	Comparative cost analysis	Cost per ton	Red.cost scope (CAPEX)	No
(Akbar et al., 2021)	Static	Comparative cost analysis	Costs per week	Cost scope	Yes
(Nordahl et al., 2022)	Static	Comparative cost analysis	Cost per leg	Cost scope	No
(S.P. Parvasi et al., 2025)	Static	Comparative cost analysis, Break-even analysis	Cost per week	Cost scope	No
(Nordahl et al., 2024)	Static	Comparative cost analysis	Cost per year	Cost scope	No
(Seyed Parsa Parvasi et al., 2025)	Static	Comparative cost analysis	Cost per TEU/week/total, Emission/tkm	Cost scope	No
(Tangstad et al., 2023)	Static	Comparative cost analysis	Cost per year	Cost scope	No
(Gribkovskaia et al., 2019)	Static	Comparative cost analysis	Cost per TEU/day	Cost scope	Yes
(Jovanović et al., 2021)	Static	Comparative cost analysis	Cost per TEU	Cost scope	Yes
(Rosas and Verduijn, 2023)	Static	Comparative cost analysis	Cost per year	Cost scope	Yes
(Kooij, 2022)	Static	Comparative cost analysis	Cost per year	Cost scope	Yes
(Wang et al., 2023)	Static	Comparative cost analysis, Optimisation based modelling	Costs for rotation of a liner service	Full scope	Yes
(Lee et al., 2021)	Semi-Dynamic	Comparative cost analysis	Cost per year	Cost scope	No
(Ammar, 2025)	Semi-Dynamic	Break-even analysis	Cost per lifetime	Cost scope	Yes
(Kooij et al., 2021)	Semi-Dynamic	Comparative cost analysis	Cost per year	Cost scope	Yes
(Ghaderi, 2019)	Dynamic	DCF	PV of personnel cost, crew cost per container	Red. cost scope (Crew)	No
(Dantas and Theotokatos, 2023)	Dynamic	DCF	NPC	Cost scope	Yes
(Kretschmann et al., 2017)	Dynamic	DCF	NPC, RFR	Cost scope	Yes
(Jovanović et al., 2022a)	Dynamic	DCF	RFR, daily costs	Cost scope	Yes

(Santos and Guedes Soares, 2018)	Dynamic	DCF, Break-even analysis	Discounted cashflows per yr., BE newbuilt price	Full scope	No
(Jovanović et al., 2022b)	Dynamic	DCF	NPV	Full scope	Yes
(Verberght and Van Hassel, 2019)	Dynamic	DCF	NPV and IRR	Full scope	Yes

Benchmarking, which involves the comparison of results to at least one reference case or baseline, represents a central analytical element across all reviewed studies. From the panel, 17 studies benchmark the autonomous vessels concept under investigation to a conventionally operated vessel. Four papers extend this comparison to road transport, while two studies compare autonomous vessels to road transport only. Methodologically, papers including a road transport reference case are conducted primarily in the context of short-sea shipping and typically adopt a shorter-term perspective. Thus, they rely on static approaches focusing on cost comparisons per period or per transported unit. This result indicates that intermodal comparisons are generally limited to operational cost efficiency and do not evaluate long-term investment performance under consideration of the time value of money.

Overall, the approaches, methods, metrics and benchmarking procedures used within the literature appear to be heterogeneous with varying levels of analytical depth or scope. This limits comparability but also complicates interpretation of reported economic implications. Furthermore, the dominant use of static and semi-dynamic methods suggests that time-dependent financial effects are often simplified or neglected, even though autonomous ship concepts appear to be capital-intense. This may render results rather conceptual and reduce practical decision relevance.

4.3 Cost estimation

This section addresses research question 3 by examining how key cost items are estimated and how these estimates are impacted by assumptions and uncertainties. Even though the cost categories were often not explicitly stated in the publications, they could mostly be deduced and mapped to the cost items from the five cost categories proposed by Stopford (2009). In a further step, it was assessed how cost items change from the respective baseline case, if the benchmark allows such a comparison (e.g., both the baseline case and the scenario use the same transport mode). The results are shown in the following tables. If the cost item is expected to increase in the autonomous shipping case compared to the self-defined benchmark, this is indicated by an upward arrow and vice versa. If the cost item is expected to be the same in the autonomous shipping case as in the benchmark, the arrow remains horizontal. Multiple arrows for an individual cost item indicate that multiple scenarios with different assumptions were made in the publication. Furthermore, the tables show how the conclusions were derived, i.e., state whether the direction of the change is a claim of the author (indicated by a ‘c’), a reference to another publication (indicated by an ‘r’) or if it is the result of the own calculations or modelling by the authors (indicated by an ‘o’). This initial mapping reveals that some cost categories receive a more widespread use among the panel while other cost categories seem to be somewhat underrepresented.

4.3.1 Operating costs

The results of the evaluation of the operating costs are shown in Table 7. With regards to operational expenditures, 15 publications expect them to decrease within their autonomous shipping cases, one publication predicts an increase or a decrease depending on the assumed operational mode, and one publication expects OPEX to stay on the same level. Four publications do not indicate an overall change but indicate changes of individual cost items. Two publications do not indicate any information about the development of total operational expenditures or its individual cost items.

The first cost item of OPEX that was investigated, was crewing, where 19 publications assume a reduction of the related costs. Five publications also expect crew-related costs such as stores and consumables to be decreasing. Alongside this reduction of crew-related costs, 16 studies of the panel claim additional costs for the ROC as a new cost item of the OPEX, from which seven studies did not disclose sufficient information on ROC cost or how their cost estimation was done. The study by Akbar et al. (2021) omits ROC costs based on the assumption that ROC cost is neglectable compared to other cost items. For the 16 studies considering ROC-related operational expenditures, the estimates are done at various levels of detail. Kretschmann et al. (2017) base their ROC cost estimate on the MUNIN project and its report (Kretschmann et al., 2015), where a detailed analysis to estimate the ROC cost per ship per year was done. This cost estimation not only includes operational but also capital expenses and is translated into a service charge within a “ROC as a service” model and is classified as an operational expense by Kretschmann et al. (2017). By Santos and Soares (2018) the ROC cost is estimated based on the assumed required crew and a rotation plan, as well as the investment cost of modern ship bridge systems, although an estimate per ship per year, or another period, is not disclosed. In Ghaderi (2019) the ROC cost is estimated based on an assumed crewing concept for the ROC and disclosed wages per crew category, whereas Jovanović, Vladimir, et al. (2022b) simply assume that the ROC cost is covered by an 50 % increase in port costs. While Kooij et al. (2021) discloses ROC cost estimates, the cost model is an adaptation of Kretschmann et al. (2015) to fit the stepwise crew reduction approach. The adapted version of the cost model, however, is not disclosed. In Rosas and Verduijn (2023) a cost model based on communication cost between ROC and ship, operational hours for the ship, captain hourly rate, and number of ships operated by the captain is provided. The remaining ten studies refer to other studies as the source for estimating ROC costs, with Kretschmann et al. (2015) being the most directly or indirectly cited source. This means that, although quite a few studies include ROC cost estimates, there are few original works performing detailed analyses to estimate the ROC cost. Furthermore, Kretschmann et al. (2015) seem to be the source of most ROC cost estimates, although some do adjustments to account for uncertainty, inflation, or a smaller fleet than what was assumed in the original work. Cost estimates for the ROC seem to be more dependent on number of ships operated from the ROC than the type of ship. For instance, Kooij (2022) assumes that the ROC cost is identical for small feeders and ultra large container ships. The large range of ROC costs used in the different cost models indicates a need for more in-depth research on this cost item and its changes within different operational concepts.

Another part of OPEX is regular maintenance works. Twelve publications assume increasing costs for maintenance and repairs. Kretschmann et al. (2017, 2015) propose a concept of performing maintenance on partly or fully unmanned ships by boarding teams, while the ship is in port. This concept becomes a necessity if no, or a reduced crew is onboard, and has the effect that the reduction on OPEX from lower crew costs is at least partly compensated by an increase in maintenance costs during the port stays. The proposed concept by Kretschmann et al. (2017) is directly referenced in seven publications (Ammar, 2025; Dantas and Theotokatos, 2023; Jovanović et al., 2022b, 2021; Nordahl et al., 2024; Rosas and Verduijn, 2023; Tangstad et al., 2023). Based on expert interviews, Kooij et al. (2021) adopt a comparable concept, that involves boarding crews for cleaning while the ship is in port and maintenance works during docking period.

While some studies integrate an increase of insurance premiums and administration costs into their calculation others set them as a constant and 14 publications do not perform an estimation of this cost item at all.

Although not directly included as cost items in Stopfords (2009) classical cost categorization, two other considered cost items were observed. First, Dantas and Theotokatos (2023) and Santos and Soares (2018) consider additional costs for data transfer, software and data analysis in the case of unmanned ships with an elevated autonomy level. Second, Lee et al. (2021) add costs for education towards their model and expect a significant decrease in this cost item in ships with a higher autonomy level as compared to a traditional ship.

The total operating costs of autonomous vessels, compared to conventional vessels, are consistently assessed to decrease. This decrease is caused by a reduction of crew, stores, and consumable costs, that are assumed to be larger relative to the estimated increase in maintenance and ROC costs. Reduced costs for crewing appear to be viewed as the most significant change in the OPEX category. While on one hand, the crew on board the ship is removed, on the other hand additional personnel is required in ROCs for operating the ship, and in ports to perform regular maintenance. While original sources for detailed estimates are scarce, it appears that a shared view is that ROC costs rather depend on the number of ships being operated from the ROC and the assumed operational mode, than on the ship type. While most panellists either do not consider administrative and insurance costs or assume them to remain the same, five panellists assume an increase in these cost items. Furthermore, it appears that a shared view is that the net personnel cost impact results in a cost reduction. However, due to the few available original works performing cost element estimation, uncertainty remains high.

Table 7: Considered impact of autonomy on operating costs.

Paper	Crew		Stores/ cons.		Maintenance/rep.		Ins./admin.		Other		ROC		Total
(Ghaderi, 2019)	r	↓	r	↓	o	↑	-	-	-	-	r/o	↑	↓
(Jovanović et al., 2022b)	r	↓	-	-	r	↑	-	-	-	-	-	-	↓
(Akbar et al., 2021)	c	↓	-	-	-	-	-	-	-	-	-	-	↓
(Dantas and Theotokatos, 2023)	r	↓	r	↓	r	↑	r	↑	c	↑	r	↑	↓
(Gribkovskaia et al., 2019)	r/c	↓	-*	-	-*	-	-*	-	-*	-	-*	-	↓
(Nordahl et al., 2022)	-	-	-	-	-	-	-	-	-	-	-	-	-
(Nordahl et al., 2024)	r	↓	-	-	r	↑	r	→	-	-	r	↑	-
(Tangstad et al., 2023)	c	↓	-	-	r	↑	c	→	-	-	r	↑	-
(Santos and Guedes Soares, 2018)	r	↓	-	-	r	↑	r/c	↑	r	↑	o	↑	↓
(Chaplin, 2019)	c	↓	c	↓	-	-	-	-	-	-	r	↑	-
(Kooij et al., 2021)	r	↓	r	↓	o	↑	c	↑	-	-	o/r	↑	↓
(Jovanović et al., 2021)	r	↓	-	-	r	↑	-	-	-	-	r	↑	→
(Lee et al., 2021)	o/r/c	↓	-	-	-	-	-	-	r	↓	-	-	↓
(Kretschmann et al., 2017) †	r	↓	r	↓	r	↑	-	-	-	-	r	↑	↓
(Verberght and Van Hassel, 2019)	c	↓	-	-	c	↓	c	↑	-	-	r	↑	↓
(Wang et al., 2023)	-	-	-	-	-	-	-	-	-	-	-	-	↓
(Alias and Felde, 2022)	-	-	-	-	-	-	-	-	-	-	-	-	-
(S.P. Parvasi et al., 2025)	c	↓	-	-	-	-	-	-	-	-	r	↑	-
(Rosas and Verduijn, 2023)	r/c	↓	-	-	r	↑	r	→	-	-	r/o	↑	↓↑→
(Kooij, 2022)	r	↓	-	-	c	↑	c	→	-	-	c	↑	↓

(Jovanović et al., 2022a)	r	↓	-	-	-	-	-	-	-	-	r	↑	↓
(Seyed Parsa Parvasi et al., 2025)	r	↓	-	-	r	-**	-	-	-	-	r	↑	↓
(Ammar, 2025)	r	↓	-	-	r	↑	r	↑	-	-	r	↑	↓

† References based on **(2015)**, which is the authors own work
* 40 % of OPEX are attributed to other expenses to operate a ship. It is not disclosed which cost items are covered
** No clear distinction can be made, since the benchmark is a truck

4.3.2 Voyage costs

As can be depicted from Table 8, 19 publications of the panel consider VOYEX in some way or another within their cost modelling, from which 16 expect a decrease in costs related to fuel. Based on the MUNIN project Kretschmann et al. (2017) analyse the impact that different aspects within the area of ship design (e.g., reduced air resistance, reduced displacement and hotel load) might have on the fuel consumption, and come to the conclusion that these have a combined effect of a reduction of the fuel consumption by 6 %. This assumption is being referenced by six publications of the panel (Akbar et al., 2021; Jovanović et al., 2022a, 2022b, 2021; Nordahl et al., 2024; Rosas and Verduijn, 2023). Dantas and Theotokatos (2023) adopt the idea of reduced fuel consumption as a result of a different ship design, and adapt a cubic formula to estimate fuel consumption. Gribkovskaia et al. (2019) take a conventional ship design as their baseline and analyses one scenario with an improved design and without any autonomy function and a second scenario that additionally makes use of autonomy functions that enable reduced crew, an increased cargo capacity and reduced investment costs, which also leads to a reduced fuel consumption for the concept designs. Depending on the scenario, Kooij et al. (2021) come up with the same or increasing fuel costs. However, they design their use case with fuel cells, or an electric propulsion system in mind, instead of combustion engines which are assumed for the base case. Closely related to a ships fuel consumption are its emissions. Emissions in cost modelling can be considered with the aid of emission prices. The cost for the emission of carbon dioxide is considered by four studies (Dantas and Theotokatos, 2023; Jovanović et al., 2022a, 2021; Verberght and Van Hassel, 2019), and in the case of Dantas and Theotokatos (2023), also nitrous oxides.

Besides fuel and emissions, port charges are another cost item of VOYEX. While eight publications expect them to remain on the same level for conventional as for autonomous ships, six expect them to rise. Again, based on the MUNIN project, Kretschmann et al. (2017) propose a concept for the approach and the departure of an autonomous ship where a boarding crew embarks the ship to control the ship during these stages. In the long-term they expect the boarding crews to be a service offered by the port; thus, they estimate an increase of the port costs or canal dues. Since the costs of such a concept has too much uncertainties around it, they assume port costs that are 20 % higher for autonomous than for conventional ships. Four other studies reference this assumption by Kretschmann et al. (2017) and include boarding teams in their cost models (Akbar et al., 2021; Jovanović et al., 2022a, 2022b, 2021). The sixth study assuming increased port charges due to boarding teams is the study by Kooij et al. (2021), who state the need for mooring crews, if no automated mooring system is installed onboard. Similar to the concept proposed by Kretschmann et al. (2017) these crews would board the ship to moor the ship in the port. According to Kooij et al. (2021) these boarding crews could enter the ship together with the pilots. Apart from Kooij et al. (2021), pilotage and towing is either assumed to be unchanged for autonomous ships (five studies) or is not addressed.

Other considered VOYEX items include an agent to monitor the cargo transactions and the bunkering of an unmanned ship in port (Kooij, 2022), and the maintenance of the main engine (Dantas and Theotokatos, 2023). The latter is an uncommon approach since maintenance is typically either included in OPEX or as a part of periodical maintenance. Jovanović, Vladimir, et al. (2022b) also show a significant deviation from all other publications within the scope of the panel, since they consider the costs for the personnel of the ROC to be part of the port charges and therefore a cost item of VOYEX.

A reduction of fuel costs is almost a consensus in the cost category of VOYEX. This reduction is mostly backed by the design of autonomous vessels, which assumes the removal of superstructure and accommodation, thus reducing wind and water drag. Additionally, these design changes allow the ship to maintain its cargo capacity at reduced dimensions and deadweight. The uncertainty around other cost items certainly is higher: while most panellists agree on port related services to remain at the same level, port charges are expected to rise in six publications due to costs for shore personnel to perform supervision of cargo operations or other work that a ship's crew typically performs in port. Original work is scarce, a large share of the panellists refers to the work of Kretschmann et al. (2017, 2015) or makes unsubstantiated claims.

Table 8: Considered impact of autonomy on voyage costs.

Paper	Fuel		Port charges, canal dues		Pilotage, towing, etc.		Other		ROC		Overall
(Ghaderi, 2019)	-	-	-	-	-	-	-	-	-	-	-
(Jovanović et al., 2022b)	r	↓	r	↑	-	-	-	-	r	↑	-
(Akbar et al., 2021)	r	↓	c	↑	-	-	-	-	-	-	↑
(Dantas and Theotokatos, 2023)	o/c	↓	-	-	-	-	r/c	↑↓	-	-	↓
(Gribkovskaia et al., 2019)	r/c	↓	-	-	-	-	-	-	-	-	→
(Nordahl et al., 2022)	-	-	-	-	-	-	-	-	-	-	-
(Nordahl et al., 2024)	r	↓	r	→	r	→	-	-	-	-	-
(Tangstad et al., 2023)	o/r	↓	r	→	r	→	-	-	-	-	-
(Santos and Guedes Soares, 2018)	c	↓	c	→	c	→	-	-	-	-	↓
(Chaplin, 2019)	-	-	c	→	-	-	-	-	-	-	↓↑→
(Kooij et al., 2021)	o/r	↑→	c	→	r	↑	-	-	-	-	↓↑→
(Jovanović et al., 2021)	r	↓	r	↑	-	-	o	→	-	-	↓
(Lee et al., 2021)	o	↓	c	→	c	→	-	-	-	-	→
(Kretschmann et al., 2017) †	r/c	↓	r/c	↑	r/c	-*	-	-	-	-	↓
(Verberght and Van Hassel, 2019)	c	↓	c	→	-	-	-	-	-	-	↓
(Wang et al., 2023)	r	↓	-	-	-	-	-	-	-	-	↓
(Alias and Felde, 2022)	-	-	-	-	-	-	-	-	-	-	-
(S.P. Parvasi et al., 2025)	-	-	-	-	-	-	-	-	-	-	-
(Rosas and Verduijn, 2023)	r	↓	r	→	-	-	-	-	-	-	↓↑→
(Kooij, 2022)	-	-	-	-	c	→	c	↑	-	-	-
(Jovanović et al., 2022a)	r	↓	r	↑	-	-	r	↑	-	-	↓
(Seyed Parsa Parvasi et al., 2025)	r	↓	r	-**	-	-	-	-	-	-	↓
(Ammar, 2025)	r	↓	r	↑	-	-	-	-	-	-	↓

† References based on Kretschmann et al., **(2015)**, which is the authors own work

* Additional services such as Pilotage are mentioned but are not considered separated from the overall port charges

** No clear distinction can be made, since the benchmark is a truck

4.3.3 Capital costs

CAPEX as the third large cost category are discussed in 20 studies. This is shown in Table 9. A significant difference here is related to whether a newbuild or a retrofit is considered, or if the ship concept is uncrewed or not. Studies comparing conventional and autonomous ships investigate cost differences, typically by having a conventional reference ship from which cost deviations are considered. There are a few studies comparing autonomous ships to road transport only, in which the CAPEX estimates are not considered as a cost change relative to a reference ship, and a comparison is not stated or cannot be differentiated by the given information.

Eleven studies from the panel expect an increase for the newbuild price of the ship. Kretschmann et al. (2017) expect newbuild prices for autonomous ship to be 10 % higher than those for conventional ships. This is due to additional ship technology and redundancy of systems required for unmanned operation, that cannot be offset by the cost reductions for the removal of the deckhouse and the hotel system. It is also noted that uncertainty clouds the estimation of investment costs of autonomous ships and that some professionals expect investment costs to become lower than for conventional ships in the long run. Kretschmann et al. (2017) is referenced by five studies (Akbar et al., 2021; Ammar, 2025; Jovanović et al., 2022a, 2022b, 2021), although increases in the newbuilt price assumptions vary between additional 5 % and 10 % for the autonomous ship. Dantas and Theotokatos (2023) also expect rising investment costs, but base their expectation around their own claims and works, although the argumentation is quite similar to Kretschmann et al. (2017). By discussing other works, Rosas and Verduijn (2023) assume that cost for autonomous technology in the retrofit of a barge would be 150,000 €. Lee et al. (2021), setting up their own cost model, base their assumptions on the newbuild price of conventional ships of similar type and size as in the autonomous cases. Although they use higher investment costs for autonomous ships, they do not disclose clearly how that assumption is made. Based on a master's thesis by Frijters (2017), the study performed by Kooij et al. (2021) assume higher investment costs for crewed autonomous ships, while for uncrewed autonomous ships they expect reduced investment costs. In a later publication, Kooij (2022) also assumes that the newbuild cost of unmanned ships will be lower than for conventional ships due to the changes of the ship design (e.g., deckhouse and hotel load). Although they do account for the additional cost of new autonomous systems, this does not set off the decreases due to the altered ship design, resulting in total lowered CAPEX, thus coming to a different conclusion than Kretschmann et al. (2017).

Kooij et al. (2021) also note that changes in investment costs have an impact on interest and depreciation as well. Six studies also consider an interest rate and a total of seven additionally include the residual value of a ship as part of the calculation of the net present value. Since the interest rate depends entirely on how a ship is being financed, it is not further considered within the scope of this literature review. The same holds true for the residual value, where the duration of a depreciation and a potential residual value may be influenced by regulatory bodies and authorities. Although not entirely part of a ship's operation, but rather a service component supporting the operation of unmanned ships, four publications in the panel also explicitly consider the investment costs of the ROC. This contrasts with an indirect consideration of ROC-related investment costs via service charges in a "ROC as a service" model. From a ship operator's perspective, these charges are mostly classified as OPEX and have been discussed in Section 4.3.1.

Changes to capital expenditures revolve around the initial investment costs. The majority of the panellists assume the initial investment of autonomous ships to be higher than conventional ships. This increase is justified with autonomous technology and new ship designs. Individual publications add that initial investment costs could be reduced with maturing technology in the future. The impact of financing is covered via interest rate and residual value, although financing is not expected to change in an autonomous shipping case. Concluding, the change in the cost category CAPEX for autonomous ships remains highly uncertain. This is because a majority of publications base their assumptions on Kretschmann et al. (2017, 2015). Thus, the apparent consensus among the panellists that CAPEX will increase is a result of one paper's assumption propagating through the literature creating the impression of an established fact.

Table 9: Considered impact of autonomy on capital costs.

Paper	Initial purchase		Interest rate		Residual value		ROC		Overall
(Ghaderi, 2019)	-	-	-	-	-	-	r	↑	-
(Jovanović et al., 2022b)	r	↑	-	-	c	0 $	-	-	↑
(Akbar et al., 2021)	r	↑	-	-	-	-	-	-	↑
(Dantas and Theotokatos, 2023)	o/r/c	↑	r	↑	c	0 $	-	-	↑
(Gribkovskaia et al., 2019)	-	-	-	-	-	-	-	-	-
(Nordahl et al., 2022)	o	-*	-	-	-	-	-	-	-
(Nordahl et al., 2024)	r	-*	-	-	r	0 $	-	-	-
(Tangstad et al., 2023)	r	-*	-	-	c	0 $	-	-	-
(Santos and Guedes Soares, 2018)	-	-	o/c	→	o/c	0 $	c	↑	-
(Chaplin, 2019)	-	-	-	-	-	-	-	-	-
(Kooij et al., 2021)	o/r	↓↑	o	→	o	0 $	r	↑	↑
(Jovanović et al., 2021)	r	↑	-	-	-	-	-	-	↑
(Lee et al., 2021)	o/c	↑	o	→	-	-	-	-	↑
(Kretschmann et al., 2017) †	r/c	↑	-	-	-	-	-	-	↑
(Verberght and Van Hassel, 2019)	o/c	↑**	o	→	o	80k/0 $***	-	-	↑
(Wang et al., 2023)	r	-*	-	-	-	-	-	-	-
(Alias and Felde, 2022)	-	-	-	-	-	-	-	-	-
(S.P. Parvasi et al., 2025)	r	-*	-	-	-	-	-	-	-
(Rosas and Verduijn, 2023)	r	↑	o	→	-	-	-	-	↑
(Kooij, 2022)	r	↓	-	-	-	-	r	↑	↓
(Jovanović et al., 2022a)	r	↑	-	-	-	-	-	-	↑
(Seyed Parsa Parvasi et al., 2025)	r	-*	-	-	-	-	-	-	-
(Ammar, 2025)	r	↑	-	-	-	-	-	-	↑

† References based on Kretschmann et al., **(2015)**, which is the authors own work
* CAPEX disclosed, including cost of autonomy, but not differentiated to a conventional ship of same size, or comparison is with road transport
** Assumption of increased initial investment is referenced to a quote for an automated mooring system
*** 80k $ for the scrap value of the ship itself. For autonomous systems it is assumed 0 $

4.3.4 Cargo handling and periodic maintenance costs

Apart from the large cost categories OPEX, VOYEX and CAPEX, some publications also cover cargo handling costs and consider periodic maintenance costs, which is shown in Table 10 and Table 11. However, none of the panellists expect drastic changes within these categories. The assessments of cargo handling costs are based on references and claims, and as such there are no original cost estimation for cargo handling costs in the reviewed studies. The overall expectation in all studies is that cargo handling costs are expected to remain stable. This expectation stems from the assumption that cargo handling does not necessarily need to be automated for autonomous ships, and that the same equipment and port crew can be used to perform loading and offloading of both conventional and autonomous ships. Empirical evidence and models for cost estimation of non-conventional cargo handling lacks.

With regards to periodic maintenance costs, the only two studies mentioning those expect that periodic maintenance costs will be about the same for both conventional and autonomous ships.

Table 10: Considered impact of autonomy on cargo handling costs.

Paper	Loading, unloading, stowage		Overall
(Ghaderi, 2019)	-	-	-
(Jovanović et al., 2022b)	-	-	-
(Akbar et al., 2021)	c	→	→
(Dantas and Theotokatos, 2023)	-	-	-
(Gribkovskaia et al., 2019)	-	-	-
(Nordahl et al., 2022)	c	→	→
(Nordahl et al., 2024)	r	-	-
(Tangstad et al., 2023)	c	-	-
(Santos and Guedes Soares, 2018)	c	→	→
(Chaplin, 2019)	-	-	-
(Kooij et al., 2021)	r/c	→	→
(Jovanović et al., 2021)	-	-	-
(Lee et al., 2021)	c	→	→
(Kretschmann et al., 2017)	-	-	-
(Verberght and Van Hassel, 2019)	-	-	-
(Wang et al., 2023)	c	→	→
(Alias and Felde, 2022)	-	-	-
(S.P. Parvasi et al., 2025)	-	-	-
(Rosas and Verduijn, 2023)	-	-	-
(Kooij, 2022)	c	-*	-
(Jovanović et al., 2022a)	-	-	-
(Seyed Parsa Parvasi et al., 2025)	r	→	→
(Ammar, 2025)	-	-	-

* An agent in port is considered to supervise cargo handling and bunkering. In this review this cost item is considered under VOYEX

Table 11: Considered impact of autonomy on periodic maintenance costs.

Paper	Dry docking & special surveys		Overall
(Ghaderi, 2019)	-	-	-
(Jovanović et al., 2022b)	-	-	-
(Akbar et al., 2021)	-	-	-
(Dantas and Theotokatos, 2023)	o	→	→
(Gribkovskaia et al., 2019)	-	-	-
(Nordahl et al., 2022)	-	-	-
(Nordahl et al., 2024)	-	-	-
(Tangstad et al., 2023)	-	-	-
(Santos and Guedes Soares, 2018)	-	-	-
(Chaplin, 2019)	-	-	-
(Kooij et al., 2021)	c	→	→
(Jovanović et al., 2021)	-	-	-

(Lee et al., 2021)	-	-	-
(Kretschmann et al., 2017)	-	-	-
(Verberght and Van Hassel, 2019)	-	-	-
(Wang et al., 2023)	-	-	-
(Alias and Felde, 2022)	-	-	-
(S.P. Parvasi et al., 2025)	-	-	-
(Rosas and Verduijn, 2023)	-	-	-
(Kooij, 2022)	-	-	-
(Jovanović et al., 2022a)	-	-	-
(Seyed Parsa Parvasi et al., 2025)	-	-	-
(Ammar, 2025)	-	-	-

5 Discussion

5.1 Synthesis and implications for future research

The systematic review demonstrates that economic assessments of autonomous ships are conducted across diverse market and operational contexts. While it is noteworthy that all studies consider remote operations to be relevant, the specific autonomous shipping concept examined is not always clearly specified. The analysis shows that half of the contributions consider some sort of constrained autonomy, being the vessel's ability to operate independently from human intervention under certain conditions. In contrast, full autonomy was only considered in three studies. Five publications did not allow to derive the assumed operational mode, which significantly limits the comparability of results.

Methodologically, the literature exhibits a range of approaches, methods and metrics. Analyses range from simple, static cost comparisons to comprehensive investment appraisals covering the full vessel lifecycle using discounted cashflow models. It can be assumed that this diversity of methodologies reflects differing analytical perspectives, which is further evident in the choice of benchmarks or treatment of uncertainty. Consequently, direct comparisons of results must be undertaken with caution and is in many cases not feasible. Differences in the scope of cost categories considered compound this issue. The application of Stopford's framework proved helpful to map these variations, consistent with the work previously done by Ziajka-Poznańska and Montewka (2021).

Beyond these technical observations, the systematic review and detailed comparison of papers have revealed four conceptual limitations in current economic assessments on autonomous ship that may reduce robustness, comparability and practical relevance of results.

- First, empirical cost data on the investment and operation - especially of a ROC - remain scarce and the limited data available is rarely validated. As a result, model outputs rely on speculative assumptions, reducing their usefulness to evaluate business cases.
- Second, original cost estimations are frequently absent, with several studies relying on unsubstantiated claims or secondary references for key inputs of their calculations.
- Third, references are sometimes adopted without critical evaluation of the underlying assumptions allowing potential misunderstandings or any bias being propagated through the literature.
- Fourth, scientific transparency is often insufficient. This concerns the documentation of methodological choices, e.g., the inclusion of cost items or categories as well as the specification of key scenario parameters. Limited transparency prevents the reader to assess the robustness of any findings or to reproduce them.

Overall, the review supports the argument that research on the economics of autonomous ships is strongly driven by assumptions as empirical data is scarce or unavailable (Ghaderi, 2020; Ziajka-Poznańska and Montewka, 2021). Consequently, the current body of research cannot be used to draw definitive conclusions, leaving economic uncertainty unresolved and decision-makers still affected by this ambiguity. To ensure that future research provides the desired impact - reduced uncertainty - we propose guidelines for methodological rigor and transparency. Research adhering to these guidelines ensure, that they can be used to draw conclusions and achieve a better understanding of economics of autonomous ships, thus ultimately reduce uncertainty in decision-making.

5.2 Guidelines for economic assessment of autonomous ships

As outlined in the previous section, the systematic disclosure of assumptions, design choices, estimation methods, and parameter values is valuable to improve the robustness, comparability and practical value of economic assessments of autonomous ships. Such assessments typically involve comparisons across different operational and ship and autonomy concepts, and are often measured against a conventional baseline. Hence, insufficient documentation can limit interpretability and reproducibility.

To address this challenge, the recommendations summarized in Table 12 to Table 16 are proposed as a structured transparency guideline. The objective is not to prescribe specific modelling approaches, but to ensure that assumptions and decisions are disclosed in a manner that enables interpretation, and comparison across future economic assessment studies. The guideline is intended to support both authors in conducting own research and reviewers in evaluating the methodological approach and results of studies.

Table 12: Scenario definition and high-level assumptions.

Assumption or scenario element	Reporting requirement
Autonomy mode	The operational mode and level of autonomy shall be explicitly defined for each evaluated case or scenario, including the baseline. The classification scheme applied (e.g., *IMO/CCNR etc.)* should be specified and referenced.
	Any operational limitations associated with the selected autonomy mode (e.g., weather limits, traffic density, port restrictions) should be described.
Crewing level and concept	The crewing concept shall be explicitly defined for each evaluated case or scenario. The number of crew members and their functional roles should be specified.
	Crew rotation schemes should be described if possible.
General vessel characteristics	The principal characteristics relevant for comparison shall be specified including, type/classification, dimensions, design speed, cargo capacity.
	Special equipment affecting cost, operability or cargo capacity (e.g., onboard cranes) should be described where relevant
	The vessel flag state shall be specified.
Market assumptions and geographical scope	The market segment shall be clearly defined, including the operational pattern (e.g., liner, tramp, ferry etc,).
	The geographical scope of operations shall be defined, including relevant countries or regions.
	Assumed cargo volumes shall be specified per period and per scenario observed in the analysis.
	Revenue assumptions shall be disclosed for each scenario. If revenue is assumed identical across structurally different scenarios, this assumption shall be explicitly justified.

Table 13: Methodological choices and assumptions.

Choice or assumption	Reporting requirement
Analytical perspective	The analytical perspective, i.e., system-level or firm-level, shall be clearly introduced and aligned with the stated objective of the analysis.
Time horizon and periods	The analysis time horizon, i.e., number and length of periods shall be clearly defined (e.g., per voyage, annual, lifecycle).
	The treatment of seasonal effects (explicit modelling vs. averaging) should be described.
	The observation period shall be consistent with the assumed technical and economic lifetime of the vessel, or deviations shall be justified.
Time value of money	It shall be stated whether discounting is applied.
	If discounting is applied, the discount rate shall be disclosed and justified.
	If several periods are observed, the treatment of inflation shall be specified and justified, including whether values are expressed in real or nominal terms.
Calculation methods and metrics	The chosen economic evaluation method (e.g., static cost or break-even analysis, or dynamic discounted cashflow (DCF) techniques such as voyage cashflow analysis (VCF)) shall be clearly described.
	The economic performance indicators reported (e.g., net present value (NPV), internal rate of return (IRR), required freight rate, payback period) shall be specified.
	Where relevant, both absolute and relative performance indicators should be reported to enhance comparability.
Baseline definition	A baseline or benchmark case shall be clearly defined.
	All structural differences between the baseline and alternative scenarios shall be explicitly identified. It shall be clearly stated which parameters are varied between scenarios and which are held constant.
Uncertainty and risk	The treatment of uncertainty shall be specified, including whether deterministic or probabilistic approaches are used.
	Sensitivity analysis should be conducted for key value-driving parameters.

Table 14: Assumptions on capital expenditures (CAPEX).

CAPEX elements	Reporting requirement
New build cost	The new build cost shall be disclosed for each evaluated ship concept or scenario.
	The estimation method applied to derive new build cost shall be described in sufficient detail to ensure transparency and reproducibility.
	When comparing a conventional ship to an uncrewed ship of the same type and cargo capacity, design changes affecting construction cost should be identified and considered (changes in ship size, weight, superstructure, equipment, required propulsive power, etc.).

Additional autonomy related investment elements	All investment cost elements that differ from the baseline due to autonomy shall be identified and disclosed for each evaluated case or scenario.
	Major autonomy-related components (e.g., sensor systems, autonomy software, communication systems) shall be itemized or clearly categorized.
	Where relevant, investments in automated or autonomous port operations (e.g., mooring systems onboard or ashore) should be separately identified and linked to corresponding operational assumptions.
Energy and propulsion technologies	If changes in energy systems or propulsion technologies are assumed across scenarios, the associated investment cost effects shall be disclosed separately from autonomy-related investments. Where feasible, cost impacts attributable to changes in fuel type or propulsion system shall be distinguished from other cost drivers.
Remote Operations Centre	It shall be stated whether ROC costs are included as a CAPEX element. The classification of ROC costs as CAPEX shall be justified.
	The ROC investment cost model shall be transparently described, including main cost components (e.g., infrastructure, hardware, software, facilities). This includes the allocation method across multiple vessels if applicable (including the number of vessels served.)
End-of-lifecycle assumptions	Assumptions regarding residual value, scrap value, and/or decommissioning costs shall be disclosed.
Financing assumptions	The financing structure applied (e.g., equity ratio, leverage) shall be disclosed if it affects the capital cost calculation. If financing conditions differ across scenarios, this shall be explicitly justified.
	Interest rate, cost of capital, or opportunity cost assumptions shall be disclosed.
Other CAPEX elements	Any additional CAPEX elements included in the analysis shall be identified and described along with the estimation approach.
Total CAPEX	The total CAPEX for each evaluated case or scenario shall be reported. The aggregation method and cost structure shall be described in sufficient detail to enable reproducibility of results.

Table 15: Assumptions and on operational expenditures (OPEX).

OPEX elements	Reporting requirement
Crew costs	The crew cost estimation method shall be transparently described.
	All wage components and employment-related costs (e.g., travel, insurance, training, social costs) shall be included and disclosed.
	The assumed crew nationality and/or flag state context influencing wage levels shall be disclosed.
Insurance, admin and general costs	Insurance, administrative, and general costs shall be included and disclosed for each evaluated case or scenario.
Maintenance and repairs	The cost model used for estimating maintenance and repair costs shall be described.
	Structural changes in maintenance strategy (e.g., condition-based maintenance, increased shore support) shall be identified.

	Assumptions regarding reliability or failure rates influencing maintenance cost should be disclosed.
Stores and consumables	Stores and consumable costs shall be included where relevant and the estimation approach disclosed.
Remote Operations Centre	It shall be stated whether ROC-related operational costs are included. The classification of ROC expenses as OPEX shall be justified.
	The ROC operational cost model shall be transparently described, including major cost components (e.g., staffing, IT services, communication infrastructure, maintenance). This includes the allocation method across multiple vessels if applicable (including the number of vessels served.)
Other OPEX elements	Any additional OPEX elements included in the analysis shall be identified and described along with the estimation approach.
Total OPEX	The total OPEX for each evaluated case or scenario shall be reported. The aggregation method and cost structure shall be described in sufficient detail to enable reproducibility of results.

Table 16: Assumptions on voyage expenditures (VOYEX).

VOYEX elements	Reporting requirement
Fuel consumption and cost	The method used to estimate fuel consumption shall be described for each evaluated case or scenario.
	It shall be disclosed how differences in ship design and operational concept influence fuel consumption estimates. Examples include differences in resistance (e.g., wind, waves, hull characteristics), differences in consumers (e.g., non-propulsive loads or auxiliary consumers associated with crewing level or autonomy systems) or different operational profile (e.g., sailing speed, routing, weather exposure)
	If identical fuel consumption is assumed across structurally different ship concepts, this assumption shall be explicitly justified.
	The assumed fuel or energy cost per unit shall be disclosed, including price basis and reference year.
Port charges and canal dues	Port charges and canal dues shall be defined and disclosed for each evaluated case or scenario.
	Any differences in port-related costs due to operational mode or crewing level shall be explicitly identified and explained. If additional port services are assumed (e.g., shore-based maintenance, security, cargo handling responsibilities), these shall be defined and the estimation method disclosed.
Pilotage, towage, and related services	Costs related to pilotage, towage, and comparable services shall be defined and disclosed for each evaluated case or scenario.
	Any differences attributable to operational mode or crewing level shall be explicitly explained.
Remote Operations Centre	It shall be stated whether ROC-related voyage costs are included. The classification of ROC expenses as VOYEX shall be justified.
	The ROC voyage cost model shall be transparently described, including major cost components (e.g., staffing, IT services, communication infrastructure,

	maintenance). This includes the allocation method across multiple vessels if applicable (including the number of vessels served.)
Other VOYEX elements	Any additional voyage-dependent cost elements considered shall be identified and described. Typical additional elements (e.g., mooring crew, port security, temporary boarding crew) should be explicitly considered where relevant.
Total VOYEX	The total VOYEX for each evaluated case or scenario shall be reported. The aggregation method and cost structure shall be described in sufficient detail to enable reproducibility of results.

Table 17: Assumptions on cargo handling and periodic maintenance.

Cost elements	Disclosure requirement
Cargo handling	It shall be stated whether cargo handling costs are included in the analysis. Cargo handling cost estimates shall be disclosed, including the estimation method or data source.
	Any changes in cargo handling costs attributable to operational mode or crewing level shall be explicitly identified and disclosed for each evaluated case or scenario. If identical cargo handling costs are assumed across structurally different scenarios, this assumption shall be explicitly justified.
Periodic maintenance	It shall be stated whether periodic maintenance costs (e.g., dry-docking, class surveys, scheduled overhauls) are included in the analysis. Periodic maintenance cost estimates shall be disclosed, including the estimation method or data source.
	Any changes in periodic maintenance cost attributable to operational mode, crewing level, or maintenance strategy (e.g., extended survey intervals, condition-based maintenance) shall be explicitly identified and disclosed. If identical periodic maintenance costs are assumed across structurally different scenarios, this assumption shall be explicitly justified.

6 Conclusion and outlook

Autonomous ships represent a relatively new phenomenon in shipping, characterized by extensive claims about its societal, environmental and economic impacts. Given the substantial financial burden required to deploy and operate autonomous cargo ships, an understanding of the economic viability and dynamics is a critical research priority. This paper has set out to capture the current state of peer-reviewed research on the economics of autonomous ship operation. It does not attempt to synthesize economic outcomes of the panel but rather reviews how the results are derived and reported. Utilizing a systematic literature review, a panel of 23 studies with economic assessments of autonomous cargo vessels were identified as eligible for the analysis. The analysis is guided by three research questions: (1) in which markets and operational contexts does the literature study the implications of autonomous shipping concepts on the economics of ship operations, (2) in which way and by what methods are the costs of autonomous ship operation assessed and (3) how key cost items are estimated and how are they impacted by assumptions and uncertainties.

The review directly shows that with regards to the markets and operational contexts, economies of autonomous ships are studied within various market segments with a strong emphasis on coastal or short-sea shipping alongside inland waterway transport and deep-sea shipping. A strong regional research interest in Europe is evident in most of the studies. Regarding autonomy concepts, the analysis indicates that constrained autonomy is the dominant operational mode prevailing in research, while full autonomy currently plays a minor role.

Methodologically, the panel shows some variation, with a large share of the panel employing static methods. Besides those, dynamic methods and semi-dynamic methods find application as well. While static and semi-dynamic methods are mostly performing simple cost comparisons, dynamic analyses always discount cashflows.

Concerning assumptions around key cost items, the major cost categories CAPEX, OPEX and VOYEX are used throughout most studies. A scarce use of revenues in models highlights the current research focus around the costs of ownership and operation of autonomous ships. Crew costs are shown to be the single cost item being most impacted by autonomous ships. They consistently decrease through the panel. This is offset partially by increases in ROC costs and maintenance due to new operating concepts. VOYEX are generally estimated to decrease as well due to reduced fuel costs based on improved ship design. Estimations on other voyage related costs such as port and pilot fees show a more granular variation. Because autonomous ships are unique designs and the technology required is extensive, investment costs and therefore CAPEX across the panel are estimated to increase for autonomous ships at the current technological maturity level. However, no detailed cost estimation of the CAPEX of autonomous ships was observed within the panel, which means that uncertainty for this cost item remains high. The analysis also showed that, in general, few original works exist on the development of key cost items.

Extending the scope of the research questions, the structured approach of the literature review highlighted four shortcomings in current research, that slowed down or impeded the analysis: (i) empirical cost data, if available, is scarce and lacks external validation, (ii) frequent reliance on unbacked claims, speculative assumptions, and secondary references for key inputs, (iii) adoption of references without evaluation of the underlying assumptions, and (iv) a lack of transparency in reporting the high level assumptions of the scenario, the methodological choices and the definition of key input values. These shortcomings set a limit to the comparability of results, to the reproducibility of the research and to produce a synthesis of the findings.

Delving into interpretation, the four shortcomings together may lead to the risk of assumptions of singular studies being propagated through the literature and being mistaken as facts. Given the lack of empirical cost data on autonomous ships, relying on assumptions will continue to be a necessity for future research. However, to overcome the shortcomings associated with this, it is crucial that methodological approaches and assumptions are disclosed appropriately. Therefore, we proposed a comprehensive transparency guideline for future economic assessments of autonomous ships, that supports a standardized reporting of assumptions, methodological choices and the estimation of key input parameters. The guidelines aim at improving robustness and comparability in the body of research to support informed investment and operating decisions in autonomous shipping.

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Appendix

A1. Keyword string

TITLE-ABS-KEY (autonomous AND (ship* OR vessel) AND (econom* OR revenue OR cost OR financ*)) AND (LIMIT-TO (LANGUAGE , "English")) AND (EXCLUDE (DOCTYPE , "dp") OR EXCLUDE (DOCTYPE , "er") OR EXCLUDE (DOCTYPE , "no") OR EXCLUDE (DOCTYPE , "ed") OR EXCLUDE (DOCTYPE , "bk") OR EXCLUDE (DOCTYPE , "sh")) AND (EXCLUDE (SUBJAREA , "BIOC") OR EXCLUDE (SUBJAREA , "MEDI") OR EXCLUDE (SUBJAREA , "NEUR") OR EXCLUDE (SUBJAREA , "PSYC") OR EXCLUDE (SUBJAREA , "HEAL")) AND (EXCLUDE (EXACTKEYWORD , "Oceanography") OR EXCLUDE (EXACTKEYWORD , "Autonomous Underwater Vehicle") OR EXCLUDE (EXACTKEYWORD , "Underwater Acoustics") OR EXCLUDE (EXACTKEYWORD , "Submersibles") OR EXCLUDE (EXACTKEYWORD , "Motion Planning") OR EXCLUDE (EXACTKEYWORD , "Antennas") OR EXCLUDE (EXACTKEYWORD , "Air Navigation") OR EXCLUDE (EXACTKEYWORD , "Unmanned Aerial Vehicles (UAV)") OR EXCLUDE (EXACTKEYWORD , "Sensors") OR EXCLUDE (EXACTKEYWORD , "Collision Avoidance") OR EXCLUDE (EXACTKEYWORD , "Ocean Currents") OR EXCLUDE (EXACTKEYWORD , "Algorithm") OR EXCLUDE (EXACTKEYWORD , "Network Security") OR EXCLUDE (EXACTKEYWORD , "Drones") OR EXCLUDE (EXACTKEYWORD , "Inspection") OR EXCLUDE (EXACTKEYWORD , "Model Predictive Control") OR EXCLUDE (EXACTKEYWORD , "Predictive Control Systems") OR EXCLUDE (EXACTKEYWORD , "Object Detection") OR EXCLUDE (EXACTKEYWORD , "Robots") OR EXCLUDE (EXACTKEYWORD , "Electric Ship Equipment") OR EXCLUDE (EXACTKEYWORD , "Artificial Intelligence") OR EXCLUDE (EXACTKEYWORD , "Reinforcement Learning") OR EXCLUDE (EXACTKEYWORD , "Agent-based Model") OR EXCLUDE (EXACTKEYWORD , "Autonomous Underwater Vehicles (AUV)") OR EXCLUDE (EXACTKEYWORD , "AUV") OR EXCLUDE (EXACTKEYWORD , "Genetic Algorithm") OR EXCLUDE (EXACTKEYWORD , "Image Processing") OR EXCLUDE (EXACTKEYWORD , "Infill Drilling") OR EXCLUDE (EXACTKEYWORD , "Autonomous Underwater Vehicles (AUVs)") OR EXCLUDE (EXACTKEYWORD , "Autonomous Underwater Vehicles]") OR EXCLUDE (EXACTKEYWORD , "Optical Radar") OR EXCLUDE (EXACTKEYWORD , "Global Positioning System") OR EXCLUDE (EXACTKEYWORD , "Accident Prevention") OR EXCLUDE (EXACTKEYWORD , "Orbits") OR EXCLUDE (EXACTKEYWORD , "Controllers") OR EXCLUDE (EXACTKEYWORD , "Radar") OR EXCLUDE (EXACTKEYWORD , "Path Planning") OR EXCLUDE (EXACTKEYWORD , "Naval Vessels") OR EXCLUDE (EXACTKEYWORD , "Digital Storage") OR EXCLUDE (EXACTKEYWORD , "Aircraft") OR EXCLUDE (EXACTKEYWORD , "Seismic Acquisition"))

A2. Panel evaluation scheme

General information/bibliometric data

Variables	Description

Author(s)	Authors of the study
Title	Title of the paper
Year	Year of publication
Journal/source	Name of the journal or conference
Publication type	Type of publication
Affiliation	Does the paper state an affiliation to a research project or funding scheme?

Considered MASS concept

Variables	Description
Ship type(s) and transport concept	What ship types and operational concepts does the study investigate?
MASS concept, RCC and crewing level	How is the MASS concept described and what is the operational mode?
Operational environmental and geographical scope	What operational environment (e.g., Deep-Sea, Short-Sea) and geographical scope does the study define?
Institutional scope	What institutional scope does the study define?

Research design

Variables	Description
Type of research	How can the study be defined in terms of how data is gathered on a spectrum between purely theoretical/conceptual work and purely empirical work?
Data sources	What primary data (sources) are used for the study?
Methods and criteria used for cost analysis	How is the time value of money account for by the author? What kind of calculations are made and what KPIs derived?
Covered periods	Are single or multiple periods covered and if latter, was discounting used?
Metrics and sensitivity analysis	Which metrics were used for the evaluation of MASS and was a sensitivity analysis conducted?
Cashflow scope	Which revenue and cost categories were analysed in the study?
Benchmark	Does the study compare MASS with traditional ships?

Considered aspects of the shipping cashflow model

Category/variables		Description
Ship revenue impact	Cargo capacity (ship size, bunkers and stores)	Does the study consider changes on revenue potential brought by MASS?

	Productivity (operational planning, operating speeds, off hire time, utilization, port time)	What assumptions have been made and results been obtained?
	Markets (freight rates, market balance, quality of service, competition, new market opportunities)	
	Other	
Operating costs	Crew (wages, travel, insurance)	Does the study take into account the changes in operating costs brought about by MASS? What assumptions have been made and results been obtained?
	Stores / consumables (general stores, lubricants)	
	Maintenance / repairs	
	Insurance / administration / general charges	
	Other	
Voyage costs	Fuel costs	Does the study take into account the changes in voyage costs brought about by MASS? What assumptions have been made and results been obtained?
	Port charges, canal dues	
	Pilotage, towage, mooring	
	Other	
Cargo handling costs	Loading, unloading, stowing	Does the study take into account the changes in cargo handling costs brought about by MASS? What assumptions have been made and results been obtained?
Periodic maintenance costs	Dry docking and special surveys	Does the study take into account the changes in periodic maintenance costs brought about by MASS? What assumptions have been made and results been obtained?
Financing costs	Initial purchasing costs	Does the study take into account the changes in financing costs brought about by MASS? What assumptions have been made and results been obtained?
	Financing costs (interest, debt repayment, dividends)	
	Residual value	

Other

Variables	Description
Key quotes related to costs by the authors	Does the study include "key quotes" that may be worth being included in the text?
Main limitations presented by the authors	What relevant limitations with regards to the topic our paper do the authors present?
Future research suggestions	What relevant suggestions with regards to the topic our paper do the authors present?
Any other comments	(Open variable for any additional remarks)

Declaration of interests

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

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: