Complexity ahead: a comment on shipping futures and new research frontiers

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Abstract

Shipping mobility futures are complex, interacting with multiple innovation systems and components of society, not least the connection of the local with the global. This commentary focuses on the key future trends in shipping and outlines some of the research agendas that might arise from this. Decarbonisation will be crucial in an industry that is set to grow, meaning that technical and social approaches to abatement will be necessary. However, demand prediction is uncertain due to changing geopolitical narratives and policy measures that address environmental damage. The latter presents a significant governance challenge in an international industry. This will be supported to some extent by increasing digitalisation that will enable more robust monitoring and efficient operations. Ultimately, how these transformations play out in places such as ports will impact the global marketplace and measures for Greenhouse Gas emissions. The commentary concludes with potential future research agendas.

Key words: shipping, decarbonisation, digitalisation, ports, governance, sustainable transition

Introduction

In an increasingly globalised world has brought to the fore the interplay of global, local, and how these places come to be connected. Shipping has a key role in moving products and people, but with an increasing need to decarbonise how societal functions are delivered, there are necessary systematic changes taking place. Energy security has increasing significance due to geopolitical pressures, and commodity shortages have increased the price of everyday goods, in which the cost of their transportation remains key. Different ways of organising markets, including direct purchases from producing countries will change the relationship between consumer and shipping. This commentary focuses on the key trends and likely future research agendas that will influence the shipping industry in the coming decades; aspects such as decarbonisation, changing shipping practices, governance of a global industry, digitalisation and regional transformation will be key themes.

Decarbonisation in the context of growth

The shipping industry is a central function of the global economy – transporting goods across the world and facilitating international supply chains. 95% of goods are transported by vessel, and shipping contributes around 3% of global greenhouse gases (GHGs). There is, however, international legislation mandated by the International Maritime Organization (IMO) that sets targets of 'near zero' by 2050, including well-to-wake emissions. Shipping is more cost efficient method than aviation to transport goods, particularly as shipping tends to be sympathetic to volume. Whilst aviation generates a higher level of carbon, shipping's overall impact on the environment is higher due to the low-grade fuel that is utilised creating more greenhouse gases (GHGs) and byproducts that include sulphur dioxide, nitrogen oxide and particulates.

Yet still, global trends suggest that demand will increase across all types of shipping to transport food, goods, leisure craft and cruise ships for the new middle classes (Benamara et al., 2019). This shipping trend suggests that the seemingly obvious solution for GHG reduction of reducing the number of miles sailed is unlikely, and with the continuing paradigm of 'cheap' products linked to a political narrative of the cost-of-living crisis the continuation of globalised value chains seems likely for some time. This then makes vessel efficiency and greening of fuel a priority. However, the paradigm of 'cheap' products is also a prohibitive factor for fuel decarbonisation, with many low-carbon fuels costing several times that of conventional marine oil. As a result, there are a range of co-ordination requirements to facilitate technology uptake and acceptance. This is further complicated by the international nature of actors within the shipping industry and a risk-averse culture (Mäkitie et al., 2022).

In the mid-term to 2050, decarbonisation will be the maritime industry's preoccupation, influencing strategy and investment. It is broadly accepted that there will be a multi-fuel future, this is due to the heterogeneity of vessels and their journeys. This introduces a complexity to encouraging change as multiple markets will need to be facilitated simultaneously. At present, energy density and speed of charging make battery-electric unlikely for long-haul shipping (Stolz et al., 2022) and modelling often shows biofuel to have the highest emissions (Horton et al., 2022). The front-running fuels are green ammonia and green hydrogen that will be made utilising renewable energy electricity. There are numerous socio-economic challenges to the uptake of alternative fuels (Griffiths et al., 2021; Norris et al., forthcoming) and these will influence

aspects of the shipping industry including length of journeys, governance arrangements, and regional transformation. Digitalisation will play a supporting role in alternative fuel uptake.

Predicting demand and voyage change

Demand forecasting is a particular challenge in the shipping transition, whilst all models predict growing demands, none converge (Naghash et al., 2024). This is likely due to the diverse factors that influence demand. Where GDP increases typically correlate with shipping increases (goods and leisure craft) there are factors such as public awareness of environmental concerns now leading to increased local purchasing. Policy interventions will also have an impact, be they security of supply, curtailing consumption, or environmental protection measures. Urbanisation, population growth and megacities have roles to play, with emerging activity in developing countries such as Africa, Asia and South America (Blaci and Surucu-Balci, 2021).

Forecasting tools will also need to evolve to understand how shipping may change with the use of new fuels. Due to the lower energy density of alternative fuels, shorter vessel journeys may be necessary, or route dictated by the availability of fuels in particular ports. Further, the way goods are shipped and charged may change as the lower energy density of fuels means that vessel space usually dedicated to goods will change purpose. However, there have been capacity developments in Panama and Nicaragua that will allow the use of larger vessels which in turn will generate cost reductions. This will reduce the number of port calls which will limit costs but will require increasing feeder transport as part of the supply chain.

This outlines just some of the main interacting factors that impact the ability to forecast. There are limited projections past 2050, where it is hoped that the shipping industry would be carbon neutral. Currently, the industry is not on track to hit 2030 targets (Baresic et al., 2024) yet it is crucial to understand what shipping demand might look like beyond this point to pick the most appropriate solutions and understand how many generations of each technology is required. Indeed, technologies such as waste-to-energy were previously dismissed in the UK as once in a generation technology as recycling targets would eliminate waste. Sweden, however, pursued waste-to-energy and now concurrently needs to and is able to import waste from other countries including the UK.

Environmentally there would be a net benefit if trading and therefore shipping practices returned to a focus on semi-local and seasonal trade. Shorter trade routes would mean that energy density would not be such a barrier and food goods would be fresher. Alongside the above-mentioned predictive challenges, it is striking that should shipping continue unabated the pollution and damaging practices will contribute to rising sea levels. This in turn may discount ports or routes, contributing to further forecasting challenges.

Governance of this mobility transition and accountability

Governance has a crucial role to play in managing the transformation of shipping futures. However, the very nature of this globalised industry makes co-ordination complex due to multi-level governance and competing goals. Significantly, the Paris agreement which focused on

national emissions excluded the shipping sector due to the lack of consensus of how emissions would be addressed from this international industry. The IMO as the international regulator was attributed oversight of the industry and the is subsequently developing an increasingly robust legislative framework. However, this exclusion from the Paris agreement is attributed by some as a factor in shipping's slower rate of transformation. Commentators have also attributed shipping's distance from the public gaze as another reason for the absence of transformation pressure until recent years. It is also a hard-to-abate sector due to its long investment schedules and ship lifespans of 25 to 30 years.

Vessels are registered in different countries, known as the vessel's flag state. Around 40% of the world's fleet are flagged in Panama, Liberia or the Marshall Islands whilst these countries own less than 1% of the world's fleet. The converse is true for Japan, South Korea and the USA with 25% ownership and 5% flag-state status. A relatively equal share of ownership against flagging is found in Europe (32%/19%) and China (13% /12%). Since 2010 there has been significant growth of EU ownership and flagging, stimulated by a change in taxation schemes in many EU countries, outlining the competitive nature of vessel flag registration where competition could be based on safety, environmental and labour regulations. This said, international minimums are set, and it is important for future mobilities and vessel decarbonisation as the EU is cited as one of the most advanced technically, legislatively, and fiscally for maritime decarbonisation.

It has been shown that the shipping sector is subject to volatility from multiple sources, examples include the 2007 – 2008 economic crash, Covid-19, the Suez Canal obstruction in 2021, or the low water levels of the Panama Canal in 2025. There are multiple ways within which ship owners and operators will seek to smooth out activity. One such way is flag-switching or flagging-out, which is registering the vessel under a flag different to the nationality of its owner or switching flag states. This is done to maximise profits and flexibility, through (in)direct cost reduction through zero or nominal tonnage-based taxes, registration fees and the flexibility to employ cheaper crews, and more relaxed regulations for vessel operations, accompanied by a reduced probability of being inspected by a port authority and the associated delays that would be caused by this (Chondrokouki and Tsekrekos, 2010).

It may be possible that despite growth in EU flagging, environmental performance legislation and penalties may lead to increased flag switching behaviour with vessels being registered in less stringent flag states. Questions arise as to how this may be discouraged, the primary option would be the unification of legislation, but other options may include utilising port state control to inspect vessels. However, a notable barrier is the second-hand vessel market, where vessels are sold to flag states with less stringent requirements, any legislation that is introduced would need to be conscious of devaluing these vessels so that they become scrap – it might be asked which would be the most carbon intensive outcome. Possible solutions could be tiered legislation dependent on cargo or vessel route; this would be environmentally preferable to long legislative timelines to allow for long vessel lifespans.

The need for control also points to a need to develop a system of accountability, with an absence of granular data a significant challenge in the shipping industry. Yet with what entity does over-sight responsibility rest with? The IMO plays a central role in facilitating global negotiations around what decarbonised shipping futures may look like. Research shows the

IMO's limited power to enforce legislation (Bach, 2023), instead seeking to achieve consensus – this has led to tensions between countries in low-lying regions who are at risk of rising sea levels and countries reliant on shipping for much of their goods. This leads to the question whether a new organisational or legislative framework is required to meet this challenge.

Digitalisation of the shipping industry

Growing digitalisation holds many promises within the maritime industry, be it increasing the availability of data that is easy to collate and compare, or the automation of functions on vessel, at port, or throughout the supply chain. The growing level of digital technology integration will be evidenced in increasing levels of automation, the integration of shore-based and sea-based operations, and electronic data replacing paper documentation. At the same time, this will introduce a growing need for security and establishing protocols with respect to data access and intellectual property rights amongst other issues.

Alongside these more habitual uses of digital technology, there are also opportunities for disruptive innovations (Haralambides, 2019; Legorburu et al., 2022). Studies have coalesced around a few key areas of the digital shipping industry – Maritime Autonomous Surface Ships which are automated and autonomous vessels; smart vessels that are integrated with smart fleets and smart ports; and ultra-low emission vessels on inland waterways and at sea (Oloruntobi et al., 2023). It is thought that with increasing digitalisation that the waterborne supply chain will become increasingly seamless, with intelligent vessels and ports communicating real-time data to reduce congestion, waiting times and costs (Pfeifer et al., 2020; Oztanriseven and Nachtmann, 2020; Zhang et al., 2022). The intelligence of vessels could even extend to speed matching to align with harbour slots or automatically adapting to port congestion and weather conditions (Sullivan et al., 2020). HERE

Further, increased data sharing would allow for harmonisation between flag states and higher levels of control and accountability. As such, the increasing ease with which data can be collected, stored and shared will be instrumental to support the proliferation of environmental protection and the increased data and monitoring that will be required to ensure compliance. The key areas will include tracing of green fuels including bunker certification, and attributing the type of fuel used at which point in the voyage and others. Also, this increased data would lead to higher co-ordination and predictability meaning that ports would be better able to support the energy transition by balancing bunkering and charging capabilities for electric vessels. However, increasing digitalisation may bring about changes in flagging as automation reduces labour requirements, and vessels have tended to be flagged in states with lower labour costs.

Ports, policy and place

With a growing shipping industry, associated infrastructure will need to expand, including the size and location of ports as there will be increased throughput, larger vessel sizes, and increased transportation and bunkering of a larger variety of fuels. It can be surmised that there

are two main challenges within shipping mobility futures – servicing an expanding market with associated supply chain infrastructure and limiting the impact on the environment.

Ports are heavily dependent on activities that are entrenched in fossil fuels, in their service to the shipping industry amongst a plethora of other industries that utilise their space. As a result, these locales are sites of GHG emissions, air pollutants and particulate matter (Dinwoodie et al., 2012) and other challenges such as air quality, the availability of new energy infrastructure and liaison with local communities (European Sea Ports Organisation, 2019). Indeed, 5% of total shipping emissions are found at ports (ITF, 2018) and can travel up to 500km over land, leading to adverse health impacts (Ahamad et al., 2018) meaning that the narrative of healthy shipping and healthy regions are inextricable (Chen et al., 2019).

Ports are themselves at risk of climate change. Meaning that they must undertake regional mapping of climate scenarios and consider the risk to their own supply chains (Asgari et al., 2015). There are a number of ways ports can support shipping decarbonisation such as providing Onshore Power Supply (Zis et al., 2014), bunkering alternative fuels (Styhre et al., 2017), reducing vessels' time at birth through quicker turnaround (Alamoush et al., 2020) and Just-In-Time or Vessel Speed Reduction measures (Chang and Jhang, 2016, Poulsen et al., 2018).

There is also potential for ports to engage with market-based measures. Crucially, the port state ensures legislative compliance on part of national maritime authorities (Poulsen et al., 2018). Ports can also contribute through incentives such as green berth allocation policies or penalties such as increased tariffs or ports dues for polluting vessels. Other incentives may include docking priority where time in port is costly due to associated services and lost operational time (Mjelde et al., 2019) – this would be better enabled by the increasing digitalisation of the sector. This said, whilst ports enforce and implement regulation (Cullinane and Cullinane, 2019), different ports have different powers to enact (Lam and Notteboom, 2014), this can be influenced by their status as a public, private or trust port.

Anecdotally, experts have outlined that trust ports within the UK, which are ports governed by a local independent board with local reinvestment of operational surpluses, typically engage more fully with supporting industry to decarbonise due to the ports' increased sensibilities to the future of the region and its inhabitants. In fact, experts outline that one of the main hurdles for ports in supporting shipping decarbonisation is a lack of clarity and direct intervention from governments. Due to the uncertain future for alternative fuels, ports are reluctant to make decisions as to what might be the 'winning' technology as there would be significant financial losses associated with the wrong choice. Resource leakage of regional incentives is another concern of consulted experts; however, recent literatures show that single-country incentive programmes are less effective due to additional bureaucracy – with rising complexity there is less engagement (Sköld, 2019).

Overall, research has shown that ports have a limited impact on the global value chain (Poulsen et al., 2018). However, this does not account for maritime decarbonisation and the role of ports as sites of transformation. Green shipping corridors, created by the Clydebank Declaration at COP26, are designated routes that will enable the use of zero-emission vessels by joining multiple ports to the initiative. Literature outlines the importance of local and global

experimentation coupled with strategic alliances with varying geographical proximities for scaling (Boschma, 2005) and through green shipping corridors consolidates the pivotal role that ports will play in experimentation and subsequent scaling of green shipping futures.

The infrastructural requirements of shipping decarbonisation add to the imperatives already placed on ports to address decarbonisation within their own business models. Likely areas of change will be dock, piers and channel harbours, wharves, buildings, and the inclusion of Internet of Things devices. In the longer term, it seems likely that ports will add to their renewable energy portfolio to facilitate the production of green fuels. Alongside this, ports must also support the decarbonisation of other industries that use the port space, for example the different storage requirements of electric vehicles compared to internal combustion engine vehicles. Related to this, potential technology futures may include interchangeable batteries for port vessels, much like the EV battery schemes in China; this would require additional storage and electrical infrastructure. It can be seen that ports then become sites of interruptive innovation and system transformation.

Future research directions

In short, this commentary has outlined the complexity of shipping mobility futures, which will demand a multi-disciplinary approach to solve physical science, engineering and socio-economic challenges. It seems apparent that there are many inter-connected innovation systems that influence this hard-to-abate industry. It is perhaps salient to then think of what future research is required to facilitate the much-needed transformation of the industry.

The decarbonisation of the shipping industry will be a significant challenge, research areas will include engineering and chemistry focused aspects such as combustion, engine-response and the safe integration, storage and handling on ships and on land. There are also socio-economic aspects such as encouraging the uptake of currently more expensive fuel and industry or public perception of alternative fuel production and bunkering.

The governance of this transition will be multi-level, multi country, and connected to many industries. Literature suggests that the IMO is lacking in power for the scale of transformation (Bach and Hansen, 2023), but industry narratives focus on ‘what the IMO can do to drive change’; when this is coupled with risk-aversion on the part of shipping companies, and a desire to remain competitive amongst exporting countries, this suggests that research into alternative modes of governing and organising may be needed. Further, geopolitics has a dual role to play as both an impeding (narratives of delivering goods/services at the cheapest rate) or promoting (energy security, spillovers and market-leading advantages) factors. As past crisis have established, the study of flagging behaviour may be salient, coupled with public perception of the green credentials of shipping or passenger vessels.

Digitalisation will have a crucial role to play and conducting whole-system analysis on how digital technologies will be integrated on vessels, in ports, the supply chain and the systemic change this might bring about is essential. There are on land developments such as autonomous vehicles that will change how cargo is distributed. There will be a raft of legislative and technological challenges to ensuring security of data and devices, but increased

information will allow for more efficient operations and a higher level of control. What too are the opportunities for using digital technologies to increase safety?

Not least, there are the place-based aspects to transformation, which are increasingly the subject of study. Ports are complex systems that through their dependency on internal and external factors are inherent to social, economic and environmental issues (Sifakis and Tsoutsos, 2021). Ports have a role to play in decarbonisation and economic prosperity where they can support cost and risk minimisation (Tovar and Wall, 2019; Aveta and Romano, 2020) for the industries and their regions (Defeuilley, 2019; Winnes et al., 2015a; Fenton, 2017). Ports will not be the only sites of transformation within shipping industry futures, this will include places that will host alternative fuel production, transportation, and data centres to store the increasingly granular shipping data. The role of ports in supporting decarbonisation and incentivising the shipping industry is not extensively explored and perhaps is overlooked by policymakers. What can we understand on co-ordination activities between on-site port carbon reduction and trade-offs in supporting the decarbonisation of sectors that use their ports.

This paper outlines some of the key developments in shipping mobility, and suggests at some of the key areas of future research. It is important to note that shipping futures will require innovation across the fields of engineering and the physical sciences, and throughout the humanities to understand what is technologically possible and how these technologies might be integrated with society.

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