Through Life Carbon Emissions and Mitigation Opportunities

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Synopsis

The lifecycle of a ship is currently carbon intensive, with many mitigation methods focused primarily on a vessel's operational carbon emissions. However, there are significant emission reduction opportunities throughout the life cycle of a vessel. This paper investigates the through life emissions for an example hypothetical vessel; accounting for the various stages of the life cycle including build, operation, support, and disposal. Following review of the current emissions, mitigation strategies will be explored for the stages, predominantly focusing on emitted carbon but also on the ability to reduce embodied carbon throughout the life cycle.

Key words: Life-Cycle Analysis; Ship Design; Emission Mitigation

1. Introduction

The Greenhouse Gas Protocol Corporate Standard divides emissions into three categories, scope 1, 2 & 3 (The Greenhouse Gas Protocol, 2015). These all play a significant role in the emission calculations for everything, with companies choosing at what level they wish to publish. Although it should be noted that one entities scope 3 emissions may be a suppliers scope 1 emission. The different scope level definitions are defined as:

- Scope 1 – Direct emissions that are controlled or owned by a company;
  - Emissions from fuel combustion within company owned vessels.
- Scope 2 - Indirect Emissions;
  - Emissions caused by the generation of electricity within buildings or through the provision of shore power.
- Scope 3 – Indirect emissions;
  - Emissions created through the supply chain and external manufacture and provision of goods and services.

The maritime industry has previously focussed on operational emissions by using the tank-to-wake emissions of the vessel. However, this is changing. Just from the operational perspective the emissions are now well-to-wake, although it should be noted that well in this context is just the original power source (International Maritime Organization, 2019).

The life cycle of a ship is far more than just the operational aspect. The build of a conventional steel vessel has a significant emission impact due to the production of steel. Operationally the emissions are driven by the fuel, which is likely to be F76 (fossil fuel) for some time. The support of vessels is an interesting aspect as Defence are striving to be more self-reliant and reduce the logistics burden. Although this would also include upkeep and maintenance. The largest issue with the support aspect is that many vessels will undergo life extensions, these generally require significant upkeep to ensure it is possible for the vessel for continue operating for longer than designed for. Finally, the disposal of the vessel is the last area that should be accounted for. It is not ethically responsible to pass the burden onto somebody else by selling the vessel.

95% of a ships carbon emissions currently occur during the ships operational phase (The Sustainable Shipping Initiative, 2023), and this is through the combustion of non-renewable fuels, hence much of the legislation and drivers focusing on the operational phase of a ship’s lifecycle. The IMO state that the global introduction of alternative fuels and / or energy will be integral to achieve decarbonisation targets for shipping (International Maritime Organisation , 2024). With the introduction of alternative fuels, the 95% of emissions will shift towards the other lifecycle phases and drivers will have to re-focus to create more holistic long-term targets if the maritime industry is going to reach its decarbonisation goals.

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This paper explores the emissions at the various stages of the life cycle and then proposes some mitigations to support the naval sector in reducing emissions. This will be applying a Life Cycle Assessment (LCA) methodology to a 6,000-tonne naval steel hulled frigate. The paper will illustrate key activities where carbon emission controls and influences can be identified and mitigated.

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2. Life Cycle Assessment

LCA is an evaluation method that considers a product's or system's entire life cycle, taking into account the successive and interlinked stages of a product or system from conception through to disposal. LCA encompasses the assessment of the benefits and burdens of all activities that generate carbon emissions, this includes consideration of scope 1, 2 and 3 emissions. Figure 1 highlights the key stages that require assessment through an LCA.

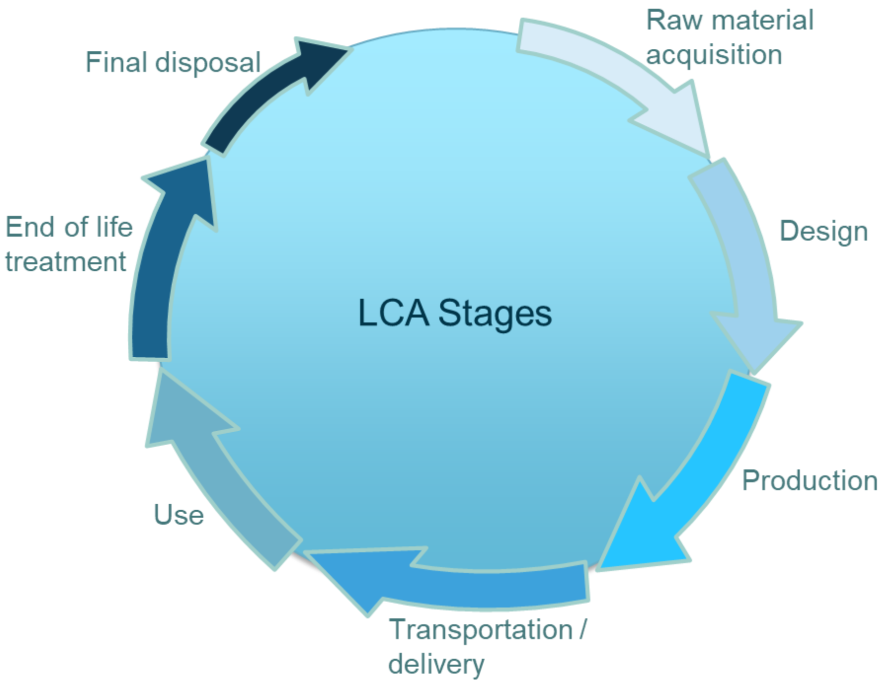

Figure 1: Stages of the Life Cycle Assessment

By considering all stages of the life cycle from raw material extraction to final disposal and or reuse, a holistic assessment of the environmental impacts can be performed.

A key part of LCA is that it does not favour one stage of a product or systems life cycle over another. As was previously stated, emphasis is often placed on the operational emissions from a ship. An LCA will give as much consideration to the emissions generated from the transportation of materials for a vessels maintenance as it does to the running of the vessel. This allows for a fair and balanced assessment and provides the opportunity to identify "environmental hotspots" that may be present in the life cycle. Emission reduction opportunities can then be identified through all lifecycle phases.

To produce a sustainable ship, there is a requirement to be a smart and responsible customer from the outset. A full analysis of the elements of the life cycle that can be controlled or influenced must be carried out and where identified this control or influence must be enacted. By assessing the supply chain and making sustainable choices in the products and services available a plethora of carbon reduction opportunities may become apparent, these could include the ability to choose different freight options (through build, maintenance and disposal activities), selection of recycled materials over new and the opportunity to use locally sourced equipment and materials. Key to this is a strong and trusted communications with the supply chain, stakeholders and service providers.

The LCA will help to ensure that environmental impacts from the whole life cycle are not ignored or transferred to another stage in the cycle. By identifying the sources of emissions, LCA enables the development of strategies to reduce greenhouse gas emissions, such as the adoption of cleaner energy sources and improved process efficiency.

3. Lifecycle phases

3.1. Design

Historically ship design has been driven by cost efficiencies in both building and operating phases, alongside compliance with minimum environmental standards. Through the onset of new regulations and growing awareness

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of climate change this is now changing. A fundamental part of this change is being applied through a change in thinking. This ensures designers are being regenerative by design, meaning that from the outset a positive impact on the overall environment has been considered. Regenerative design uses whole systems thinking to create resilient and equitable systems that integrate the needs of society with the integrity of nature.

Ships should now be designed with resource optimisation in mind from the outset, allowing for greater reuse of components, as well as choosing systems that promote repair and refurbishment over replacement.

To enable this there must be a shift of focus from one of reducing Capital Expenditure (CAPEX), which requires designers and ship owners to need to start looking at the bigger picture. An element of a design which can be disassembled easily and repurposed may initially carry a higher cost but these costs may be reduced when maintenance, mid service upgrades, end of life and environmental impacts are considered across the whole lifecycle of the vessel.

Key to a sustainable design is the ability to utilise and embrace new greener technologies. Design considerations to reduce carbon emissions through life for a large naval ship include:

- Green steel
- Wind assisted propulsion
- Air Lubrication System
- Absorption Chiller Plant
- Waste heat recovery
- Use of fuel cells for generating electricity and fresh water
- Alternative Fuels
- Carbon capture and storage
- Alternative energies (shoreside and shipyard facilities)
- Ship digitisation opportunities

This list is by no means exhaustive but provides an example of the potential carbon reduction technologies now available. Some technologies may not be appropriate for a naval vessel depending on operational requirements or technical readiness. However, by considering them from the outset designers can implement pathways to allow for future adaptations as technology evolves.

When considering the digitisation of systems, it should not be forgotten that automated systems also add an additional burden of data storage, how data is stored and managed must be considered. To put this into perspective the electricity required to store around 3,500 emails (of five MB each) produces around as much CO_2 as that from driving a compact car a kilometre and deleting 1,000 emails would give a carbon benefit of around five grams of CO_2 (Konica Minolta,, 2024).

The additional aspect to the design phase is the buildings and power that are used. Many companies are already investing in this aspect of the energy transition and as such this is deemed a negligible component.

3.1.1. Modular Design

Modularisation aims to increase the functionality of a vessel whilst also reducing repair and maintenance periods.

Modules are prefabricated which is a method of creating and producing components of a vessel off site and then delivering them to the project for them to be assembled. Within the construction industry this has proven to help accelerate construction projects and provide cost-saving opportunities, whilst also having implications for sustainability and embodied carbon, through waste reduction (University Collage of Estate Management, 2024) (V. Tavares, 2021).

The Maritime Modularity Concept is not new to navies, in a 2022 report carried out by the Royal Navy (Ministry of Defence, 2022) the benefits and risks of modularity were discussed. Whilst much of the report focusses on functionality and cost saving it does discuss the how modularity has the potential to increase the service length of a vessel (future proof), improve sustainability, improve time efficiencies (maintenance and service) and allow for increased adaptability. Whilst not mentioned in the report these benefits also have the potential to reduce carbon emissions through life.

Key to potential carbon reduction is adaptability, modular units can introduce modern technologies to a ship without the requirements of a full refit. Lessons can be learnt from this with regards to the implementation of the IMOs Ballast Water Convention (International Maritime Organisation, 2019) which states that all vessels built before 8 September 2017 will have to retrofit a ballast water treatment system that complies to the regulations standards. These standards have been mandatory for all applicable vessels on completion of their International Oil Pollution Prevention Certificate (IOPP) renewal, since 2019. For many vessels this will not be economically viable to retrofit and a surge in scrapping is being predicted (Drewery Maritime Research, 2019) (Hand, 2016).

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3.1.2. Hull Form Design

The hull design can have a significant impact on a vessels overall efficiency, the more drag it creates the more fuel it will require similarly the heavier the hull the more fuel will be required. Through applying Computational Fluid Dynamics (CFD) modelling, opportunities can be identified through the design spiral to reduce the demand for materials and improve efficiency. With the onset of Artificial Intelligence further opportunities are now being identified to realise a real-time prediction of the total resistance of the ship-hull structure in its initial design process (Yu Ao, 2023). By implementing these kind of design initiatives early on in a vessel's lifecycle designers can help to ensure that all design options are considered towards producing a vessel that is environmentally sound to operate.

Whilst efficiency is a key driver for the reduction in emissions, the only true way to meet operational net zero is by using alternative power sources. However, these efficiency gains are still required as many of the options are far less energy dense.

3.2. Consideration of the use of Raw Materials

Raw materials must be considered from the iron ore extracted for the steel hull through to the precious metals used within circuit boards and batteries. Extraction of iron ore, bauxite, copper and other minerals used in steel and alloy production is a dirty and energy intensive process. In a 2020 study carried out by Nature Geoscience they estimated that greenhouse gas emissions associated with primary mineral and metal production was equivalent to approximately 10% of the total global energy-related greenhouse gas emissions in 2018 (Mehdi Azadi, 2020).

When assessing this impact, it is imperative to note how and if the steel production and mining companies are reporting their CO_2 to ensure no double accounting is taking place.

3.2.1. Alternative Materials

A potential solution is the use of alternative materials. The increase in 3D printing has the potential to support the use of alternative materials and more efficient component designs, for example printed propellers (3D Printing Industry, 2021). There is also the possibility for hulls built from sustainable composite materials, although the scale of a large warship may not make this viable. It should be noted that these technologies are still relatively new and a lot of further analysis is required to assess their environmental credentials, especially compared against the use of recycled steel.

3.3. Lifespan and Obsolescence

Hardware, software and support equipment are all items with a shelf life. Obsolescence as defined within JSP 886 (Ministry of Defence, 2012) by the International Standard IEC 62402:2077 is the "transition from availability from the original manufacturer to unavailability". Products must be designed to be repairable and more economically viable to fix than to throw away. This can be done by ensuring that elements within equipment can be reused, repaired or refurbished, the value of the raw materials and their embodied carbon should always be considered through to disposal.

3.3.1. Design for reuse

Ship design can no longer be linear. The shipping industry needs to rethink its approach to material use and design vessels which lower emissions and close the material loop. Consideration needs to be given to all materials used, from steel hulls to copper cabling and thermal insulation. Remanufacturing is a crucial part of reducing resource depletion and a vital strategy for cutting emissions, labour, and energy, and through extending the "end-of-life" of products and their components. Remanufacturing is becoming a recognised procedure within the automotive and aerospace industries (David Parker, 2015) with some predicting that the automative remanufacturing industry will be worth USD 126.42 billion by 2030 (Fortune Bussiness Insights, 2024). When designing a vessel how equipment can be remanufactured and the processes required should be considered i.e., how easy is it to retrieve precious metals or replace components.

3.4. Build

Some studies are now stating that the contribution of ship building will soon exceed that of the service phase, with some reaching more than 50% of a vessels carbon footprint (OSK Group, 2022), (Vakili Seyedvahid, 2023). Much of a vessels carbon emission through the build and manufacture phase will be scope 3 emissions. Sustainable manufacturing extends beyond the manufacturing process and the product, to include the supply chain, across multiple product life cycles as well as end-of-life considerations.

3.4.1. Steel Manufacturing

In 2020 UK steel estimated that for every tonne of steel produced, an average of 1.85 tonnes of CO_2 are emitted. This means that steel manufacturing produces nearly twice as much CO_2 emissions as it produces steel.

Global steel production is responsible for around 7% of the world's man-made greenhouse gas emissions (Holger, 2023). However, steel is one of the most recycled materials in the world, yet the demand for new steel is currently outweighing the supply of old steel, hence a race towards the production of green steel. Green Steel utilising hydrogen technology for production is now underway in Sweden, the company involved are planning to cut emissions by as much as 95%. It is currently estimating that will produce five million tonnes of green steel a year by 2030 (Savage, 2023). According to a recent Lloyds register study the maritime industry will demand circa 17.5 Mt of steel in 2030 (Lloyds Register, 2023).

How and when the steel industry decarbonise will have huge ramifications on a vessels overall carbon emissions. Steel makes up 75-85% of a vessel by weight (The Sustainable Shipping Initiative, 2021). Going by the UK steel estimate a vessel with a 16, 000 tonne steel hull and superstructure would produce 29,600 tonnes of CO_2 in its steel production alone, to put this into context the average UK citizen currently produces around 5 tonnes of CO_2 annually (Leberton, 2023).

The technology exists to produce a greener lower carbon steel, it is now down to industry across all sectors (construction, energy, transportation, maritime) to push and build the demand alongside the onset of global regulations that recognises and incentivises the role steel production will play in the world achieving decarbonisation targets within the maritime industry and beyond.

3.4.2. Build Energy Efficiency

The building of the vessel from the component parts can take considerable energy. This is not just the metal work but there also the lifting and logistics associated within the yard. By utilising renewable power sources this could have a significant reduction in the shipyard emissions. However progress can be made by the adoption of renewable power, which would mitigate many of the emissions produced. This can be further improved by utilising alternative powered handling equipment within the yard.

3.5. Support

The support function consists of a wide range of tasks; from supply chain, fuel, cold ironing and crew transfers. The current use of support is outdated and there has been a focus on minimal build costs as opposed to the lifetime costs, for example the QEC carrier decision to be powered by fossil fuel rather than nuclear.

Optimisation of supply chains may reduce the emissions, whilst additive manufacturing should reduce this further. The ability to create spares as required rather than transport them has significant advantages. If this is coupled with digitisation and predictive maintenance rather than reactive, there could be considerable operational increase, financial savings as well as emission reduction.

Predictive maintenance attempts to foresee unplanned machinery failure, a proactive rather than reactive approach, this can often extend the life of a piece of equipment resulting in reduced disposal of equipment and increased opportunities for regeneration and reuse.

The use of cold ironing would allow vessels to no longer operate engines whilst in ports which would have a considerable impact on the emission reduction and local air quality, especially for larger vessels.

3.6. Disposal

A report commissioned by the Sustainable Shipping Initiative, exploring shipping's transition to a circular economy in June 2021 stated that global ship recycling volumes are expected to double by 2028 and near quadruple by 2033 to 28 million light displacement tonnes (The Sustainable Shipping Initiative, 2021). The World Steel Association (2023) estimates that every tonne of scrap steel used for steel production avoids 1.5 tonnes of CO_2 emissions, as well as considerable quantities of raw material (The Sustainable Shipping Initiative, 2023).

The disposal process for ships is currently carried out by the lowest bidder, how much they want to bid for the disposal contract is dictated by global steel prices and the yards processing procedures. 2021 prices varied from around $560 per light displacement tonne in Bangladesh to $300 per light displacement tonne in Turkey (Barlett, 2021). South Asia currently dominates the ship breaking industry and it is here that the ships are often beached and broken down in-situ, this regularly occurs under poor environmental and safety standards. Greater transparency and traceability of all materials is a necessity, not only to enable emission reductions through the circularity of resources, but to make ship recycling safer and more environmentally sound.

Within the UK ship recycling standards are becoming more stringent. Recycling rates by weight are high. The MOD reported that 98.4% of the material from the former Black & Gold Rover RFA was recovered and recycled with a final outturn of 8.373.230 tonnes (Minstry of Defence, 2020). A summary table from the report illustrating the waste breakdown is shown in Table 1.

Table 1 Summary of the Black and Gold Rover final waste outturn

(All figures in Tonnes)	Expected	Actual	Destination
Ferrous Metals	8.250	7.938.640	Recycled
Non-Ferrous Metals	200	150.520	Recycled
Cables	60	40.380	Recycled
Other Products	100	111.980	Sale/Recycled
Waste	150	131.710	Disposed
Total	8.760	8.373.230	

Ship dismantling and recycling is an energy intensive activity with a range of processes being applied across disposal yards. As ships become more digitised these waste streams will change creating further challenges for recycling. The American Environmental Protection Agency states that one metric ton of circuit boards can contain 40 to 800 times the amount of gold and 30 to 40 times the amount of copper that is mined from one metric ton of ore in the US (United States Environmental protection Agency, 2024). Recycling e-waste is a time-consuming process but can provide a route for economical and profitable extraction of valuable metals whilst also reducing biodiversity loss and carbon emissions.

Disposal through maintenance and obsolescence must also be considered, currently the focus is predominately on the final structure. Accountability needs to be made on equipment suppliers and designers that ensures clean disposal and reuse of products throughout a vessel's lifecycle.

More transparency is required across sectors, it should no longer be acceptable for a corporation to offload its carbon emissions through the gifting of a product. With design and manufacture should come some responsibility towards disposal.

4. Conclusions

For a shipbuilder / designer to account for their carbon each component industry must find a way to make standards quantifiable and measurable throughout a ships lifecycle. It will require collaboration and strong dialogue across all sectors. Transparency and sharing of data needs to become a positive offering from industry, the ability to share a products carbon data should be a recognised and celebrated commodity across industry from mining through to the repurposing and recycling at the end of life.

All sectors involved within the lifecycle need to take ownership of their carbon data and provide transparency to their customers in order to apply a fully holistic assessment of a ships carbon emissions. The marine industry has a stretched and complex supply chain that must be accounted for and made accountable for carbon emissions. Global regulations and multi stakeholder collaboration are essential, everyone must play their part towards shipping's decarbonisation from cabling through to hull construction and disposal.

Technology is changing fast and the ability to produce carbon neutral ships from cradle to grave is almost there. There is a wealth of carbon reduction technologies coming onto the market to support the marine industry throughout all lifecycle phases and these must be embraced and adapted where possible. It is imperative that these are considered from the outset of the ships design and that where current technology is not considered to be ready or economically viable for a design then consideration should be made to incorporate future technologies where possible. By accounting for this earlier in the phases then it can be determined where there is also an economical benefit as well.

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