Advancing Unmanned Surface Vessel Design: A Circular Economy Response to Global Conflict Evolution

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Synopsis

This paper explores the application of Circular Economy (CE) design principles to enhance the sustainability of Unmanned Surface Vessels (USVs) in the defence sector. It investigates the strategic benefits USVs can bring to maritime operations, particularly in conflict zones, due to their versatility. The integration of CE principles aims to improve sustainability, operational availability, and mission readiness by focusing on five key metrics: recyclability and repair, waste and emissions reduction, longevity optimisation, part count reduction, and design for disassembly.

Keywords: Circular Economy; Unmanned; Sustainability; Availability; Suitability

1. Introduction

The growing concern over global environmental issues is driving the implementation of a Circular Economy (CE) framework in the defence sector. Traditionally focused on operational and strategic goals, the sector now sees the potential of CE to help meet environmental targets and build supply chain resilience. This paper explores how the integration of CE principles within the design and operation of Unmanned Surface Vessels (USVs), can reduce resource consumption and enhance operational versatility.

USVs are crucial in current global maritime operations, they are capable of monitoring vast areas, gathering intelligence and tracking threats with no limitation on availability due to human welfare requirements. They are essential for tasks in conflict zones where there is a high risk to life, such as mine countermeasures, electronic warfare, and decoy purposes.

As the market shifts towards greater reliance on USVs, integrating CE principles becomes even more poignant. This analysis focuses on the environmental and economic benefits of adopting sustainable practices, particularly in hull construction, propulsion systems, and battery technologies. Through an examination of current practices and future possibilities, the paper aims to provide ideas for sustainable development in the defence sector.

2. Circular Economy

CE is an innovative economic framework that aims to transform the current global practices of creating, consuming, and disposing finite products. The objective instead is to create infinite solutions that generate economic, social, and environmental benefits.

The defence sector has already recognised CE has the potential to address environmental targets, the UK Ministry of Defence has stated in their Strategic Sustainability Action Plan to strive to build CE principles into defence designs by 2025 (MoD, 2021), through weighting acquisitions to products optimised to reduce emissions, largely to address the UK Defence's environmental target of net zero emissions by 2050. These targets are driven by the Paris Agreement, an international treaty adopted by the United Nations in 2015 to keep global temperatures rising more than 2°C between 1900 and 2100. Exceeding this limit would result in devastating economic and humanitarian impacts, including rising sea levels and extreme weather events. Predictions indicate that if the global temperature rises by 2.4°C by 2100, a 1.4 metre rise in sea levels would result in $460 billion in direct costs from land loss and forced migration, and up to 12% welfare losses in regions such as Southeast Asia (Pycroft, Abrell, & Ciscar, 2016).

While environmental impact has previously not been a driving factor for defence acquisitions, it is becoming an increasingly necessary consideration to ensure military operations and infrastructure are resilient to environmental disruptions. Introducing more sustainable initiatives in the defence market will also bring additional

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advantages such as cost savings from reducing material waste, new revenue from circular product services, rapid technology innovation, increased collaboration with stakeholders, enhanced resource security, and the attraction of top talent that are environmentally conscious.

The impact sustainable changes in the defence sector could have, should not be underestimated, the US Department of Defence's CO2 emissions in 2017 was 1212 million tonnes, this is greater than the entire output of Sweden for the same year (Crawford, 2019). In 2023 the US Department of Defence accounted 80% of the federal government emissions and the defence sector in the UK accounts for 50% of government (Bowcott, Gatto, Hamilton, & Sullivan, 2021). Introductions of sustainability initiatives to address defence emissions could offer significant cost savings to the sector and environmental benefits globally.

The economic benefits of introducing sustainable initiatives in the defence sector have already been demonstrated. The Dutch Ministry of Defence used to incinerate uniforms costing the country €500,000 a year, in 2017 they collaborated with their uniform and equipment suppliers to repair and reuse uniforms and personal equipment, saving the Ministry approximately €8 million annually (Soufani, Tse, Esposito, & Kikiras, 2018).

3. The role of USV in current geopolitical conflicts

A study by the BlackRock Investment Institute detailed that three of the highest geopolitical risks globally are conflicts likely to involve significant marine operations: Russia's invasion of Ukraine affecting the Black Sea, US-China tensions impacting the South China Sea, and Gulf tensions involving the Strait of Hormuz (Donilon, Aldrich, & Lee, 2024).

The conflict between Russia and Ukraine at the Black Sea has shown a high increase on the use of USVs for reconnaissance and strike actions from both parties. Meanwhile, tensions in the Gulf have shifted to the crisis in the Red Sea, where in February 2024, three USVs prepared to be launched in a strike mission were detected and destroyed by US forces, indicating the need for heightened security measures to safeguard the Red Sea (U.S. Central Command, 2024). This presents an opportunity for US allied forces to deploy unmanned systems in the region for surveillance of international shipping lanes. Both conflicts in Ukraine and Red Sea are setting the scene for the use and development of USVs in the South China Sea for intelligence, surveillance, and strike operations near the disputed Spratley Islands. Future potential conflicts are driving the interest for Medium and Large USVs with greater payload capacity and endurance, this paper largely focusses on Small USVs that are most commonly used currently.

4. Current USV Market

As navies worldwide recognise the strategic advantages offered by USVs, driving requirements for their design and operations become well established. The pace for delivery of USVs must match the pace of the threats in the conflicts today, highlighting an important and well known requirement in the military world, modularity. A modular design approach delves into the functionality of the platform divided into specific, scalable, and reusable modules within a vessel. This design approach prioritises the development of common modules, akin to "Lego blocks", which constitute standardised sections of the craft. These modules can be seamlessly utilised across different mission profiles and adjusted in scale as required. Furthermore, the design facilitates quick installation of self-contained mission modules, enhancing flexibility and operational agility (Schank, et al., 2016). Modularity in USVs is currently focused on the types of payloads that can be carried and exchanged, including sensors, armament, and electronic warfare modules.USVs are also often required to operate at different sea conditions and mission profiles, demanding a, not only modular, but a robust craft that is also designed to operate covertly and strike when needed.

The Unmanned Systems Integrated Roadmap FY2011-2036 lists the main challenges that USVs face and, hence, the areas of which the US Department of Defence want to enhance in such vessels (Winnefeld, Jr. & Kendall, 2011). These are focused on the improvement of the autonomous systems within the craft, power and propulsion to achieve higher ranges, communication systems improvements and, more importantly for this paper, interoperability. Interoperability focuses on facilitating cross-domain service reuse through a centralised service repository, aiming to incorporate common interfaces, components, and systems from various platforms into USV production, with the goal of achieving a platform manufactured from 80% reusable components and systems.

The desire for interoperability improvement aligns with the proposed implementation of circular design principles to USV design. Such principles emphasise on creating platforms that prioritise ease of maintenance to enhance availability, facilitating quicker supply chain responses and suitability for different requirements. A CE approach will also promote sustainability on the manufacture, life cycle and operation of the USV.

5. Implementation of Circular Design Principles

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When optimising USVs to reduce waste, performing Life Cycle Assessments (LCA) on existing and new designs is crucial for targeting sustainability initiatives to make impactful changes. AI can facilitate this, as demonstrated by Audi's use of AI to audit its supply chain, ensuring high environmental and ethical standards are met (Audi, 2019). The defence sector will faces challenges with using AI tools to perform LCAs as data security, integration with legacy systems, and regulatory compliance will likely prevent the effecitve use to generate detailed supply chain analysis.

An LCA of a typical maritime autonomous platform highlighted fuel consumption, hull construction and battery systems are the largest contributors to USVs environmental impact (Sanchez, Papaelias, Marini, Gjeci, & Marquez, 2021). The following CE principles will be considered in this section to reduce the environmental impact of the highlighted USV components; recyclability, waste reduction, longevity optimization, part count reduction, and design for disassembly (Charter, 2019).

5.1. Recyclability

The dominant material used to manufacture small USV hull forms is glass or carbon fibre. This is due to the low cost of glass fibre and the high strength to weight ratio of carbon fibre. However, recycling composite materials presents considerable challenges when compared to metals and plastics. The intricate structure of the composites makes the separation of matrix and fibre an arduous process (Shuaib & Mativenga, 2017).

Two techniques can be used for the recycling of composites, mechanical and thermo-chemical. The latter is split into fluidised bed processes, pyrolysis and solvolysis. Due to the low price of glass fibre and the degraded mechanical properties of the fibre when recycled through thermo-chemical processes, mechanical recycling is the most predominantly used method. Thermo-chemical processes are preferred for the recycling of carbon fibre composites, due to the high value of the material (Oliveux, Dandy, & Leeke, 2015). The energy consumption estimations of each of these processes can be seen in

Table 1.

Table 1 – Energy consumption estimations for each composite recycling process. The values are in range, as these vary depending on the speed that he machines operate (Wong, Rudd, Pickering, & Liu, 2017)

Recycling Process	Energy Consumption (MJ/kg)
Mechanical reduction	0.3 – 2
Fluidised bed process	6 - 40
Pyrolysis	30
Solvolysis	63 - 91

While mechanical reduction significantly reduces energy consumption, it fails to effectively separate fibre from resin, leading to material property degradation. Consequently, concerns regarding performance limitations restrict the market for the resulting material. On the other hand, pyrolysis and solvolysis are available for commercial exploitation and both techniques can output high quality recycled carbon fibres (Oliveux, Dandy, & Leeke, 2015) at the price of a high energy consumption.

Since the recycling of glass and carbon fibre structures is proven to be energy intensive to retrieve materials of sufficient quality for remanufacture, other options should be considered such as thermoplastic polymers commonly used to produce small crafts. High-density polyethylene (HDPE), which offers a simpler and less harmful solution to its recycling process and presents itself as a viable option for small USVs to fit within the UK Defence target of net zero emissions. HDPE recycling involves processes to reclaim and prepare the material for its reuse. It is then shredded to increase its surface area, helping the melting and extrusion of the material into pellets. The pellets can be sold for reuse in the manufacturing of new HDPE materials such as sheets and 3D printing filament. The simple recycling process reflects on its total energy consumption of only 1.6MJ/kg (Bataineh, 2020). In addition, recycled HDPE's mechanical properties remain similar (Chong, et al., 2017). Recycling HDPE into sheets preserves its integrity, and while 3D printing with recycled HDPE has been validated, minor issues may arise primarily from the printing technique rather than the material properties.

When assessing the recyclability of USVs, it is essential to consider not only the hull material but also the installed components, with batteries being a key component, required for providing hotel power and in some cases propulsion as well.

High density lithium ion batteries are the most common type of battery supplied to the defence sector, which contain cobalt, one of the EU's top 15 critical materials. Over 70% of the global cobalt supply comes from the Democratic Republic of Congo and 70% of the lithium ion battery market is manufactured in China. This concentration in the supply presents risks such as exclusive trade agreements and strategic supply constraints.

Additionally, the lithium ion battery demand is set to surge as electrical vehicles popularise, forecasts estimate demand shall exceed supply by 2030 (Bille, 2024). Investing in recycling could protect the national supply, but lithium-ion battery recycling is intricate, involving complex separation processes and handling of flammable electrolytes and reactive metals. Current recycling methods, hydrometallurgy and pyrometallurgy, use chemical and thermal treatments to recover batteries, which are energy intensive and rely on the use of additional raw materials, which isn't sustainable. Direct recycling is a simpler method where the cathode is extracted from the battery with minimal disassembly, re-energised with lithium, then reintroduced to the battery.

Studies suggest direct recycled cathodes can match the performance of new ones (Xu, et al., 2020) and the method is cost effective when recycling over 3000 tonnes annually (Lander, et al., 2021). As resources dwindle and battery designs evolve for easier disassembly, direct recycling is expected to become more profitable. Direct recycling emits 25% fewer greenhouse gases than pyrometallurgical and hydrometallurgical methods and producing a direct recycled cathode releases about half the greenhouse gases as producing a new cathode (Xu, et al., 2020). This data highlights the potential new battery recycling technology has to create a sustainable and economically viable endless battery supply for defence. Establishing a closed loop supply of batteries within country could enhance national security by ensuring a reliable source of essential equipment for USVs. Given the strategic importance of electrifying USV propulsion systems to achieve low acoustic signatures for critical missions, ensuring a steady supply of batteries is paramount. Closed loop battery recycling aligns with environmental sustainability goals set by multiple governments, which is increasingly prioritised in defence strategies. By minimising waste generation and reducing the carbon footprint associated with battery production, investing in direct recycling supports sustainability efforts while enhancing operational resilience.

HDPE recycling generates broader advantages by decreasing lead times and improving operational availability. Battery recycling technology has great potential to enhance national security; however, further research and development is required to enhance direct recycling profitability.

5.2. Minimise Waste and Emissions

When opting for HDPE for a USV hull, it is essential to consider its manufacturing advantages, especially regarding the potential utilisation of 3D printing technology. In the domain of small-scale 3D printing, addressing the recognised issues of shrinkage and adhesion inherent in the Fused Filament Fabrication (FFF) of HDPE, requires precise actions. This includes selecting suitable build plate materials and fine-tuning FFF printing parameters to mitigate void formation and counteract shrinkage caused by material crystallisation..

Adjusting these parameters, Schirmeister demonstrated the ability to 3D print a HDPE component with equivalent mechanical properties to injection-moulded HDPE, while minimising warping and void formation (Schirmeister, Hees, Licht, & Mulhaupt, 2019). This success holds promise for scaling up HDPE 3D printing and, potentially enabling the production of large HDPE components without the current challenges. It can then leverage the advantages of additive manufacturing over injection moulding for low-volume productions, particularly where lower initial costs and the flexibility for design changes are appealing for small unmanned vessels.

When compared with traditional lamination methods, 3D printing presents distinct advantages. Lamination techniques typically incur an estimated 25% waste of the total build, including fibre offcuts, resin waste, composite parts waste, vacuum bagging materials, and miscellaneous tools. A percentage of such waste can be recycled, but the remaining is discarded to landfill (Shuaib & Mativenga, 2017). With 3D printing, a contingency of 10% of the total filament material is allocated for initial setup mistakes and is fully recyclable and reusable. Large scale 3D printer companies process the waste back into usable HDPE and either feed back to their machines or sell it to other companies. This makes 3D printing attractive not only on the sustainability side but also for businesses to have minimal losses on production costs related to material wastage and reduced production and lead times.

Although waste in production is an important factor, typically, vessel usage contributes to 90% of a vessel's life cycle emissions, assuming a service life of approximately 20 years (Shuo Chen & Lam, 2022), (Burman, Kuttenkeuler, Stenius, Garme, & Rosen, 2016). This figure highlights the importance of fuel savings for economic and environmental reasons, optimising the propulsion system for specific operational profiles can help address this.

To facilitate propulsion modularity and adaptability across various mission profiles, outboard engines stand out as the optimal choice for small USVs. While these engines are typically fuelled by petrol, a limited selection are available for diesel use. By employing an interchangeable outboard approach, leveraging standardised fittings inherent to such engines, and incorporating an interface plate on the craft's transom, the USV's propulsion system can be easily assembled or disassembled with different outboard motors to suit the required mission profile. For instance, high-speed missions may necessitate a diesel-powered outboard to be fitted to the vessel, then easily exchanged for an electric alternative for low-speed, low acoustic operations, minimising propulsion system emissions. Although electric propulsion enhances platform sustainability by emitting zero emissions during operation, it introduces weight compromises due to battery requirements for power storage.

Outboard manufacturers are seeking to improve the efficiency of their engines and, subsequently, reducing the emissions of such modules. OXE Marine developed a Diesel-Electric Hybrid outboard engine, with a combination of a 300Hp diesel module attached with a 150Hp axial flux electric motor (OXE Marine, 2024). A diesel-electric outboard would enable the operator to widen the mission profile to include high speed transits and low speed covert movements, without a large impact on the equipment footprint inside the vessel. Looking at future options, Yamaha is releasing its first prototype of an outboard hydrogen engine, offering 425-450hp (Weiss, 2024), helping to reduce emissions from fuel cell manufacture and craft operation, whilst still maintaining high power outputs.

Reducing waste in platform production via additive manufacturing not only establishes a sustainable framework but also, coupled with outboard modularity, enhances the platform's suitability and flexibility for various missions.

5.3. Longevity and Repair

An important contributor to the longevity of a marine platform is the material and structural design of the craft. Hulls constructed from HDPE exhibit high strength and resistance to impact, offering protection against damage during slamming accelerations and collisions (Telak, Telak, & Niemczewski, 2023).

However, if a HDPE hull is damaged, its low melting temperature and robustness makes it ideal for conducting repairs on. Techniques like rotational welding, hot gas welding, and fusion welding can fix both small and large areas of damage. Sentinel, an Australian defence vessel manufacturer, already use rotational welding techniques to repair HDPE boats (Sentinel, 2024). These simple repair methodologies enable vessels to be quickly fixed and returned to operations, even when faced with limited resources in low infrastructure military environments.

The modular design of a USV can help facilitate prolong the usage of a vessel, by providing good access and utilising quick release fasteners, individual components and systems can be easily removed from vessels, enabling quick off craft repairs, expediting the restoration of vessels to operational status for missions.

Repairing components rather replacing them offers environmental benefits addressing defence sustainability targets. There are many electrical devices fitted on USVs such as motors, batteries, sonars, and lights which all have have high Green House Gas (GHG) embodiment levels, repairs of these items can extend product life, providing an opportunity to make substantial emission savings.

For example, a laptop with a life expectancy of 5 years has an embodiment carbon footprint of 304kgCO2, repairs that keep the laptop going beyond this life expectancy will prevent 60kgCO2 of emissions being released per year, minus any emissions associated with repairs, which for laptops is approixmately 5.9kgCO2 per repair (Privett, 2018).

Ensuring spare parts are accessible and technical support can be provided either physically or virtually, electrical device repairs can be conducted in the field, removing the need to wait on replacement devices to restore vessel funcitionality.

5.4. Decrease Part Count

To maximise the chance of mission success hull shapes should be optimised to the specific mission requirements which may include sea conditions, range, and speed. A novel approach to supplying USVs most suitable for their application is to set up a vessel supply service, a leasing scheme that would enable allied defence customers to share tailored assets, aligning with CE principles and defence strategies, of reducing resource consumption and emissions. Similar agreements like the Australia, United Kingdom, United States agreement (AUKUS) (Lejac & Rexha, 2022) demonstrate that the appetite for sharing capability internationally is growing and plausible to be implemented.

This service could provide a limited range of vessels designed for specific speeds, that could be supplied at varying readiness levels from bare boat to mission-ready platforms. The configuration options offered would use scalable standardised components and multipurpose parts, like multifunctional sensors would be implemented to reduce part count. Minimising component variation and count simplifies the supply chain, optimising procurement times and maintenance training, all helping optimise platform availability.

Operating within a restricted product range allows businesses to concentrate on minimising their environmental impact and enhancing manufacturing efficiency. As part of their service offerings, SMEs could provide fleet management solutions, creating opportunities for recurring revenue while simplifying vessel management for customers. This includes optimising vessel conditions through services like remote monitoring, diagnostics, and maintenance scheduling.

5.5. Design for Disassembly

For USVs to keep technically current and available, the ease to replace equipment is imperative. By having flexibility to change equipment, vessels can fit the most up to date technology and can easily adapt to a requirement changes from the end user. Such modularity and flexibility can be achieved through the implementation of a modular deck within the USV. The design of the deck in HDPE can be compared to a printed circuit board (PCB) design. Similar to a PCB, which functions based on the arrangement and interconnection of its components, the components within the modular deck design can be rearranged, swapped, or removed to alter the functionality of the deck as needed. Following a similar philosophy, the components within the modular deck design would be attached through the use of brackets, screws and heat-set threaded inserts. The process of attaching such inserts to the deck involves heating the insert and pressing it into a predrilled hole in the deck. The heat from the insert causes the HDPE to melt as it is pressed in place, once the plastic cools, it securely fixes insert in situ (Warren, 2021).

The USV deck would be structured in a grid pattern with inserts placed every 100mm, bespoke brackets would be made with the same pitch diameter to accommodate the fitting of modules within the vessel, allowing for easy reconfiguration. Figure 1 illustrates different arrangements plausible for the proposed modular deck design. Heat-set threaded inserts can also be utilised on the superstructure of the craft to fit equipment as desired.

The opportunity to quickly repurpose the entirety of the craft modules between roles and potentially users, improves the availability of the USV fleet and its suitability to different mission profiles. By enabling rapid adjustments to accommodate changing mission objectives or emerging operational needs, USVs can remain highly responsive and effective in dynamic environments. Furthermore, the ability to repurpose the craft without extensive upgrades or reconfigurations not only streamlines operational processes but also minimises downtime, ensuring that the USV fleet maintains a high level of readiness and operational capability at all times. This versatility ultimately enhances the overall effectiveness and value proposition of the proposed USV.

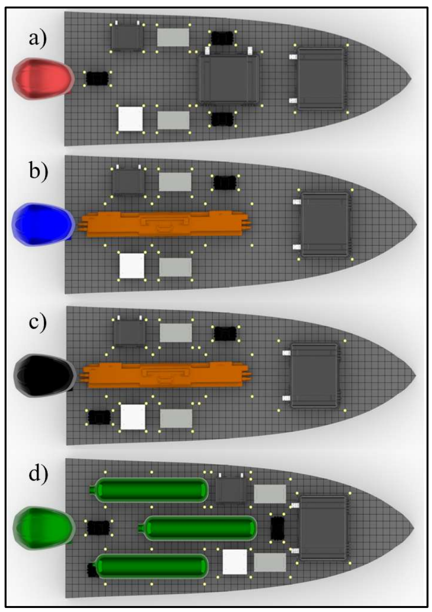

Figure 1 – Modular deck design representation. Highlighted points show which inserts would be used to accommodate decks for components in different USV's arrangements: a) Diesel version; b) Electric version; c) Diesel-electric version; d) Hydrogen version. Note: For the diesel and diesel-electric versions, the fuel tank is situated under the modular deck.

6. Conclusion

This paper highlights the importance of integrating CE principles into the design and production of USVs for the defence sector. By adopting CE principles, such as recyclability, waste minimisation, and design for disassembly, USVs can be more reliably supplied, cost-effective, less wasteful and adaptable to varying mission profiles. The focus on the recyclability of hull materials and components, along with the minimisation of waste and emissions during manufacturing and operation, contributes to environmental sustainability and national security. Additionally, the emphasis on modularity, longevity, and repairability enhances operational readiness and availability, crucial for addressing emerging threats and geopolitical tensions. Overall, the implementation of

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CE principles offers a strategic advantage by optimising resource utilisation, reducing reliance on critical materials, whilst encouraging innovation and collaboration across the defence industry.

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