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Article

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A review on the applicability of remanufacturing in extending the life cycle of marine or offshore components and structures

D.A Wahab[1], E.E. Blanco[2], A.K.A. Ariffin[1], J. Wang[2]

[1]Department of Mechanical and Materials Engineering
Faculty of Engineering and Built Environment
Universiti Kebangsaan Malaysia
43600 UKM Bangi, Selangor, Malaysia

[2]Department of Maritime and Mechanical Engineering
Faculty of Engineering and Technology
Liverpool John Moores University
James Parson Building, Byrom Street
Liverpool L8 3AF United Kingdom

ABSTRACT

One of the most significant and value added End of Life (EoL) recovery strategy in the circular economy is remanufacturing which retains the form, functionality and performance of the assemblies and structures through recovery and restoration. In the marine industry, remanufacturing is still at its infancy however there is a huge potential in implementing remanufacturing. In safety-critical industry such as marine, designing products for remanufacturing has to be integrated with reliability and safety design aspects since products and assemblies are used in a long life cycle whilst subjected to harsh environmental conditions. This paper discusses issues on Design for Remanufacturing (DfRem) and provides an insight into how remanufacturing plays a significant role in enhancing reliability and safety during the extended life cycle of marine products and assemblies, thus enabling the marine industry to contribute significantly towards the circular economy.

INTRODUCTION

In today's resource efficient and circular economy, remanufacturing has been identified as one the most promising strategy in delivering an efficient End of Life (EoL) recovery. Circular economy has been defined as an industrial system that is restorative or regenerative by intentions and design by the Ellen MacArthur Foundation (2012):

> "*A circular economy is restorative and regenerative by design, and aims to keep products, components, and materials at their highest utility and value at all times. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, and aims for the elimination of waste through the superior design of materials, products and production systems.*"

Morgan & Mitchell (2015) conducted a study on the growth of circular economy and its impact on the UK labor market, noted that one route to improving resource efficiency is to develop a circular economy as it enables products and resources to be in use for as long as possible through recovery, reuse, repair, remanufacturing and recycling. Today, the circular economy is not an option but inevitable for continued economic prosperity and ecological balance (Jawahir & Bradley 2016). The circular economy supports the three pillars of sustainable development namely the environment, social and economy by protecting the environment, providing economic benefits through increased resource security and providing new business and employment opportunities. The McKinsey Quarterly Report No. 1 (2014) as shown in Figure 1 clearly depicted the significant role of remanufacturing in the circular economy.

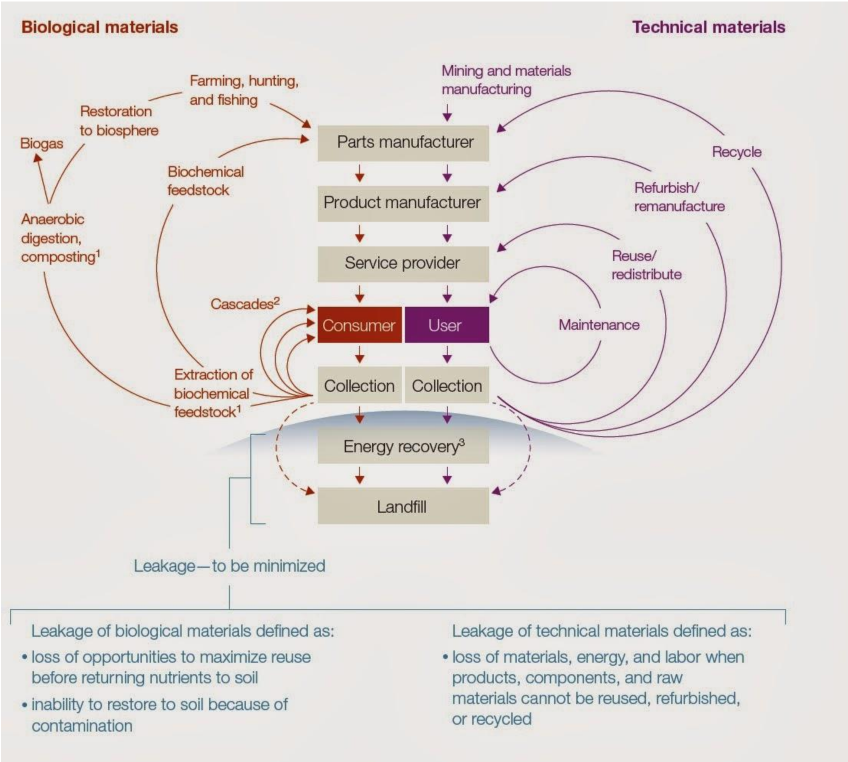

Figure 1. Shaping the Future of Manufacturing

Source: McKinsey Quarterly Report No. 1 2014

Remanufacturing gained significance after it was identified as one of the promising strategy in the 6R approach to environmental sustainability namely, reduce, reuse, recycle, recover, redesign, remanufacturing. Guitini & Gaudette (2003) defined remanufacturing as an industrial process that turns used products into products with the same quality, functionality and warranty as new products. British Standard BS8887: Part 2 defines remanufacturing as returning a used product to at least its original performance with a warranty that is equivalent to or better that that of the newly manufactured product. Through remanufacturing, products and sub-assemblies can be restored or even upgraded before entering their next life cycle.

Remanufacturing is more resource efficient than recycling and other EoL recovery strategies as it retains durable cores in the subsequent life cycles hence reducing the need to manufacture new components every time. The strategy helps to reduce CO2 emission and minimise the depletion of materials and energy. Matsumoto et al (2016) noted that since remanufacturing retains the geometric shape of products, it preserves the materials and added value embedded in the original products. The remanufacturing process involves disassembly, cleaning, inspection, restoration, reassembly and finally testing since the remanufactured products have to be given a matching warranty. A generic representation of the remanufacturing process is shown Figure 2.

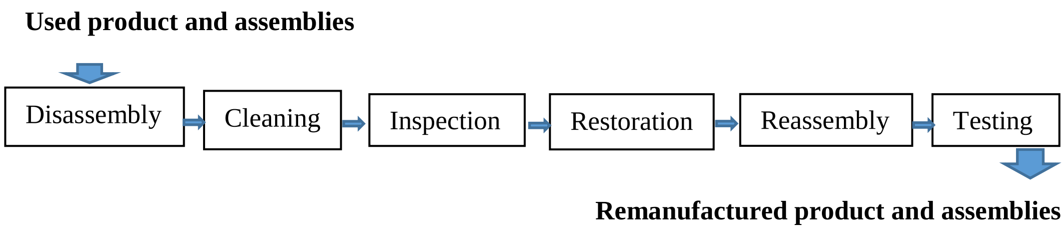

Figure 2. A generic remanufacturing process

The benefits of remanufacturing towards the three pillars of sustainable development namely environment, economics and social have been widely acknowledged and reported in literatures (Lund 1996; Sundin & Lee 2012; European Remanufacturing Network 2015; Morgan & Mitchell 2015; Jansson 2016). Since it does not involve actual production of new products, remanufacturing demands very little raw material, energy and other production inputs thus reducing the environmental impact of production. APRA-Europe (2015) conducted a study on EU 28 and reported the benefits of remanufacturing namely in its ability to reduce the potential of CO2 emissions by 400 kt. The process saves natural resources of up to 85% of raw material and using only 55% of the energy compared to that of producing a new unit. The remanufacturing industry has also provided employment opportunities in which 32,000 jobs have been offered. Remanufacturing requires highly skilled workforce as the processes involved in bringing back the components to as new conditions require compliance to standardised procedures and also informed judgements on the conditions of the incoming parts and assemblies.

CRR (2010) conducted a study on remanufacturing activity in the UK. The sectors include aerospace, automotive, catering & food, construction, ICT equipment, industrial tooling, ink & toner cartridges, lifting & handling equipment, medical, precision & optical equipment, off-road equipment, office furniture, pumps & compressors, rail industry, textiles, tyre re-treading and white goods. It was observed that the aerospace, automotive and mechanically powered machinery sectors have the largest economic impact, contributing 40%, 11% and 11% respectively to the total remanufacturing value. Remanufactured parts and components provide the same as original performance and reliability at costs typically only 50–80 % of a new. Instant availability gives customers more options at repair and overhaul time resulting in maximum productivity and lower costs (Matsumoto 2016).

REMANUFACTURING IN THE TRANSPORT INDUSTRY

The transportation industry namely aircraft, automotive, rail and marine has implemented remanufacturing as one of the end of life recovery strategy. Apart from benefitting the environment and eco-system, this strategy has impacted the socio-economy in a positive way. According to the U.S International Trade Commission (2012), remanufacturing occurs across a diverse range of industry sectors but it is more commonly concentrated among sectors that produce capital intensive, durable products with relatively longer product life cycles.

Centre for Remanufacturing and Reuse (CRR) reported that in the aerospace/aircraft industry, OEMs are heavily involved in the remanufacturing process. It is common for some assemblies and structures such as engines, avionics, landing gear, cabin interiors to undergo remanufacture at least once. It was reported that through remanufacturing, high performance products such as Caterpillar's heavy- duty engines can be remanufactured as many as six times or seven use cycles (Umeda et al 2012)

In 2010, the aerospace industry was identified as the largest single practitioner of remanufacturing by value (CRR 2010). In part this is driven by the inherently high value of the complex components involved (most significantly aero engines); however, this value is in no small degree due to overriding safety considerations that force complete overhaul or rotation of components and assemblies based on time in use, cycles or other measure of utilisation. By implication, the need for guarantees of safety implies that product performance is maintained at or near as-new level and this, in turn, implies that remanufacturing processes are relevant and prevalent. It is in the interest of aircraft manufacturers to design equipment that can be easily overhauled or remanufactured.

Today automobile parts remanufacturing is the world's largest remanufacturing sector. A recent report by The Global Industry Analyst, Inc. (2017) projected that the global market for automotive part remanufacturing will reach US$198 billion by 2024. Automotive remanufacturing is highly supported by the Automotive Parts Remanufacturing Association (APRA) which has 2000 members worldwide. Automotive parts which are commonly remanufactured include engine blocks, transmissions, starters, compressors, alternators and brake systems. Automotive remanufacturing is now a growing industry in the Asia Pacific Region, some of which are driven by relevant policies. In Malaysia, remanufacturing gained significance with the establishment of the National Automotive Policy 2014 which outlines remanufacturing as one of its technology roadmaps. Remanufacturing which is spearheaded by the Malaysian Automotive Institute has worked closely with the relevant ministry and standards body in the country in order to develop remanufacturing policy and supporting standards. Apart from automotive, activities on marine remanufacturing have also been reported in the country.

Advisen (2012) pointed out the importance of the marine transportation which has long been the dominant support of global trade and remains a crucial pillar of the global economy. The industry includes deep sea freight and cargo, barge, inland water vessel and passenger cruises. The UK Marine Industries Leadership Council (2011) reported that there are over 5,000 marine companies across the UK which employ nearly 90,000 people. The industry generates over £10bn turnover and contributes nearly £3.5bn Gross Value Added (GVA) to the nation's GDP. To date, UK is the fourth largest shipbuilder in Europe in terms of GVA and the third largest in boat-building. The report highlighted opportunities in the marine industry due to recent technology trends which calls for sustainability and user-centric design. In the EU-28 marine supplies industry, the 1st and 2nd tier enterprises employed about 390,000 people in up to about 30,000 companies (Karvonen et al 2015).

To date, the marine industry has been engaged in various efforts to ensure environmental sustainability of the industry. Advisen (2012) noted that the industry has addressed issues on oil spills by having double hull tankers, managing ballast water to avoid the spread of invasive species and most significantly working for a cleaner marine mode by minimising emissions from the use of heavier fuels. In the areas of green and efficient design, the marine industry has been engaged with activities related to the minimisation of materials consumption during ship-building, reducing the usage of energy and toxic materials during ship manufacturing, the efficient use of machinery, overall ship design improvement and reusing of ships' parts and accessories during ship maintenance (Raunekk 2010).

EoL ships may end in many different ways from shipwrecks, scrapped, as breakwaters or artificial reef or also in ship museums. However, with the increasing awareness on the need for a circular economy, the EoL strategies in the marine industry needs to managed, not solely from the perspective of environment but also for economic and social. To date, recycling is the most common EoL strategy in the shipping industry in which materials such as wood and steel are recovered as valuable materials. Some 95–98 % of ship materials by weight are recycled (ECORYS SCS Group 2009). However, recycling is the lowest in the hierarchy of EoL recovery. Apart from high energy consumption in melting and reprocessing, recycling leads to a downgrade in material quality and usability in the subsequent life cycles. Current trends in the use of lightweight composite materials will certainly have an impact on the efficacy of marine recycling in the future.

The UK Marine Industry Technology Roadmap (2015) proposed measures on energy efficiency and environmental protection for waste and ballast water management through design for reuse for component lifetime and retrofitability. According to Oakdene Hollins (2014), the term 'remanufacture' or 'refurbishment' are not usually associated with ships. Retrofitting or refitting is a more common term in the marine industry. Retrofits or upgrades, enables ship owners to adapt their existing vessels to rapid market changes, thus making them more flexible and sustainable in response to new safety and environmental regulatory demands (ABB 2017). The Scottish marine industry have been reported to conduct extensive retrofitting, refurbishment and upgrades on assemblies including diesel engines, lifeboats, vessels, buoys and also wooden hull (Oakdene Hollins 2014). Karvonen et al (2015) however argued that the idea of remanufacturing is not to refit products or product parts for the same user but to systematically take back the end of life goods and reuse them or their components for new users.

ERN (2014) conducted a study on the remanufacturing industry and noted that the marine remanufacturing industry is relatively small compared to other transportation industry such as the aerospace and automotive. It was postulated that this is likely due to much of the maintenance, repair and conversion activity are more in the repair and refit domain that is, not to the level of rigour of remanufacturing in which a warranty is given for every remanufactured component or assembly.

According to Khalid (2016) the marine industry provides a potentially attractive platform for remanufacturing. It is a global industry which utilises a wide range of vehicles (such as ships, trucks and stackers), equipment (cranes, engines and pumps) and parts which have to meet stringent technical standards. The author further justified the economic logic of marine remanufacturing which has been hit hard by the global recession that started in 2008 and proposed the use of remanufactured products to reduce dependency on expensive imported products.

Karvonen et al (2015) noted that in the marine industry, systemic changes in product design, customer attitudes toward remanufactured products, business models and value networks are needed. It was further suggested the need for technology, system creation and business development on topics including design for multiple life cycles, value addition through remanufacturing and network creation and management. Jannson (2016) provides a review on the benefits, challenges and opportunities of implementing remanufacturing in the marine domain. Opportunities for remanufacturing during the different types of ship repair was also discussed in the paper. Despite highlighting several challenges in the implementation of remanufacturing in the marine industry, the paper concluded on the potential of implementing remanufacturing in the marine industry.

DESIGN FOR REMANUFACTURING IN THE MARINE INDUSTRY

The design of a product or assemblies has a large influence on remanufacturing efficiency. Many researchers have highlighted challenges in remanufacturing and among those challenges is product design (Steinhilper 1998; Nasr & Thurston 2006). Product design affects remanufacturing efficiency in many ways and it is therefore crucial for the product to be designed with remanufacturing in mind. CRR (date unknown) noted that many products are best suited for remanufacturing however they are often not designed for remanufacturing, causing difficulty in disassembly, replacement of individual components and testing. Charter and Gray (2008) defined DfRem as a combination of design processes whereby an item is designed to facilitate remanufacturing. Nasr and Thurston (2006) noted that the full societal benefits of remanufacturing (reduced energy and material consumption and reduced wastes) cannot be achieved unless Design for Remanufacture becomes an integral part of the product development process.

ERN (2017) conducted an extensive study on remanufacturing which was funded by the EU Horizon 2020. The study as reported in the ERN D6.3 provided targeted recommendations for identified barriers in remanufacturing implementation which are categorised into three themes namely Business Models, DfRem and Process. Business models addresses the need for capital investment, customer awareness and perceptions and legislations, while Process addresses among others, the lack of control on core collections, reverse logistics, quality of core and process efficiency. DfRem addresses issues related to demand for remanufactured products, knowledge of DfRem principles, and integration of EoL learning into product design. CRR (2010) has earlier reported on a remanufacturing study among the UK industry and observed that one of the technical barriers to remanufacturing is product design that leads to difficulty in sorting and disassembly, which are key processes in remanufacturing.

The quality of returned cores are among the uncertainties associated with core acquisition in the remanufacturing industry which are due to various environmental conditions, time lengths and intensities on how the products are used (Guide, VDR 2003). To date, issues on core quality which is related to core design and development have received much interest among researchers in the field of study. A recent study by Karvonen et al. (2015) on remanufacturing barriers among the Finnish industry has shown two biggest challenges namely, cost associated with the remanufactured products in general

(45%) and another on product features and specification that is, products have not been designed to be remanufactured at the end of their useful life (45%). Oakdene Hollins (2014) had earlier noted that poor DfRem, particularly where remanufacturing is not embedded within the OEM culture, can inhibit remanufacturing. Proper decisions during the design process can mitigate barriers that occur during the remanufacturing process (Matsumoto 2016).

Remanufacturing process efficiency will be affected if the product was not designed with remanufacturing in mind, more so for independent remanufacturers who have limited access to product knowledge undertake reverse engineering in order to effectively remanufacture the product (ERN 2017). The need to bring a part or assembly to as `new condition` with the same function and performance posed several challenges which includes ensuring durability and reliability of cores, ease of cleaning, ease of inspecting the condition of the cores, ease of disassembly and reassembly of parts, ease of repair and restoration, and ease of testing.

CRR (2010) suggested some common features influencing suitability for remanufacture namely high intrinsic value, good durability, low to moderate technological evolution, availability of cores, and integrated sales/service/upgrade options and availability of design information. Common features that are detrimental to remanufacturing were also identified namely, poor design for assembly/disassembly, proliferation of materials in construction, status-dependent, fashionable items, poor perception of standards/branding, low price of new goods and craft skill shortage. However, a recent study by ERN (2017) has highlighted the need to promote products that are suitable for remanufacturing. Lack of knowledge on remanufacturing and remanufacturable products could be the one of the reason why remanufacturing did not take off in some seemingly potential industries.

Nasr and Thurston (2006) noted that sustainable product design such as DfRem will become more important since more companies are beginning to adopt sustainable product strategies, technology and design practices. For the marine industry, DfRem is not only important to ensure products features are environmentally sustainable, it will also ensure overall sustainability of the marine industry since remanufacturing will ensure a good supply of durable and quality cores into the marine remanufacturing industry. Through DfRem, issues related to high remanufacturing costs on extensive processes for disassembly, cleaning and restoration of components and assemblies due to poorly designed features can be minimised.

In the marine industry, DfRem must take into consideration the environmental conditions that these components have to undergo during their useful life. That includes prolong use, harsh environmental conditions and loadings, impact of salinated sea water, cold sea water that lead to component failures such as cracks, wear and tear, and corrosion. In the marine industry, aspects of reliability and safety are of utmost importance. The Global Industry Analyst (2017) observed that in the recent past, the durability and quality of products are consistently improving, eventually making remanufactured automotive parts equally competitive as a substitute to brand new parts on the market.

The following section addresses remanufacturing and reliability requirements and practices from the product design perspective. Several design challenges have to addressed to ensure seaworthiness in terms of reliability and safety of remanufacturable marine components. Existing design decisions at the configuration and parametric design stage may be complementary or conflicting due to the need to integrate several DfX, in this case remanufacturing whilst ensuring reliability and safety of the remanufactured components and assemblies.

Remanufacturing is only possible when there is a substantial supply of durable cores. As such at the design stage, it is vital for the right materials to be selected to ensure that cores are durable for use in the next life cycle. Durability can be generally defined as the ability of the cores to withstand wear, tear, corrosion or other forms of decay during their useful life, which are the effects of prolong use and also environmental conditions. For example, in shafting and propeller, failures include cracks on blade edges, bent blades and also surface roughness (SpiralWeld Ltd. 2017). It is therefore necessary for suitable materials to be identified to ensure durability by understanding the physics of failure namely the common mode of failures, their mechanisms and how these failures can be mitigated to support life cycle extension through remanufacturing.

Disassembly is necessary in remanufacturing in order for parts and components to be individually inspected and restored. The guidelines on Design for Dissassembly and Reassembly is aimed at enabling parts to be disassembled and reassembled efficiently without causing any damage, otherwise these parts and components will only be deemed suitable for recycling or even disposal. ERN (2017) noted that remanufacturing can be inhibited by poor design that do not support ease of disassembly. The type of fasteners used in assemblies have a large implication on ease of disassembly and reassembly, and also durability and reliability of assemblies and structures. In the marine industry, apart from welding and other mechanical joining process such as bolting and riveting, adhesive bonding is widely used especially when plates are too thin to be welded, or a particular material combination cannot be welded or for aesthetic reasons (Weitzenbock 2012). Despite the availability of Design for Disassembly guidelines such as the minimisation on the number of fasteners, easy removal and accessibility to fastening points, they may not be applied extensively during the design stage (Soh et.al 2014).

Cleaning is an important step in the remanufacturing process therefore, it is important for the component's physical form be designed to facilitate cleaning. Cleaning is aimed at facilitating inspection and damage correction (Gamage et al 2013). With the correct method for cleaning, the actual condition of the components and assemblies can be ascertained before the right repair and restoration methods be identified. Gamage et al (2017) pointed out seven factors that makes cleaning a costly process and those related to the technical aspects are part complexity, material, excessive debris and corrosion. Design decisions at the configuration design stage is crucial to facilitate the cleaning process.

Inspection is aimed at ascertaining the conditions of cores, part and assemblies. Brent and Steinhilper (2004) noted that in contrast to new-product manufacture, where sampling methods are often used, remanufacturing always requires 100% inspection and that explains why remanufactured products appear to have a better reliability than new products. Errington and Childe (2013) noted that inspections are performed at different stages of the remanufacturing process. Firstly, inspection and testing are conducted on cores in order to remove those that are uneconomical or impossible to manufacture followed by part inspection and testing to remove non-reusable components from the product. The final inspection stage is to ensure that the products are in full working order. The authors highlighted the impact of the inspections towards enhancing reliability of the product at component and systems level. SpiralWeld Ltd conducted visual inspections to detect and examine flaws such as corrosion, surface cracks, surface discontinuity on joints such as welds and seals. In addition, metal composition of components such as stabilizer stocks are also analysed using XRF.

Restoration is aimed at returning cores to its original form and performance. Guha (2009) noted that in remanufacturing, it is necessary to ensure that the original dimensions are not distorted nor the material composition sacrificed. In the pneumatic and hydraulic industry, repair and restoration involved surface finish, machining operations and also surface and heat treatment. SpiralWeld Ltd reported that restoration on their propeller shafts are carried out by overlaying high nickel alloy on damaged areas and slow cooling in thermal insulation and finally finish machined to standard dimensions. Stern seals are also restored through pre-weld machining, overlaying with high nickel alloy and finally finish machined. The restoration process and treatment must allow for the components to retain their quality and reliability as in the original specification.

Testing is an important process in remanufacturing as it determines the performance of the products and assemblies before a warranty is issued. SpiralWeld Ltd reported the different methods used to inspect and test their remanufactured products including the use of NDT methods such as dye penetrant to prove weld integrity in propeller shafts and ultrasonic examination on stern seals.

Designing products for reliability and safety are well supported by established approaches and methods from the concept design through to the embodiment design and detail design phase. For remanufacturable products, reliability requirement is even more critical since these products have to perform as in new condition after undergoing rigorous inspection, testing and restoration. Safety has always been an important consideration for remanufactured products in many industries like aerospace, automotive and medical, governed by specific industry regulations. As such, certification in order to guarantee the safety of the remanufactured products is vital (ERN 2017). Remanufacturing is to date, the best EoL recovery strategy that demands a warranty to products' original specification. This formal certification of the remanufactured product will ensure that it fulfils the functionality and safety performance in the subsequent life cycles. At the configuration design stage, several design decisions are made to ascertain the reliability of the assemblies and structures. Component selection and physical configuration affects reliability in many ways. Selection of durable materials and reliable components with higher load bearings, the use of appropriate fasteners, identifying disassembly and reassembly methods and sequence and also ensuring accessibility are typical design decisions at the configuration design stage. At the parametric design stage, the performance are established through various DfX approaches, failure analysis and testing.

Design for Maintenance is directly related to reliability and safety. With good maintenance, the condition of the parts and components can be monitored and retained. From the perspective of maintenance, design aspects related to accessibility, design complexity, part replacement and testing are important considerations. In engineering design, rules on designing for maintenance are well established. Taylor (date unknown) pointed out design for maintenance rules such as the need to modularise where appropriate, avoid the use of permanent fastening techniques (adhesive fastening, riveting or welding) where separation of components will be required for maintenance, allow easy access to units with the lowest life expectancy and those requiring routine lubrication or visual inspection. However, design rules may be conflicting depending on the purpose of the design. It is therefore necessary to carefully select the appropriate design for maintenance rules to support remanufacturing. From the perspective of design architecture, whilst modular seemed to be the best to support maintenance for remanufacturing, it does contradict with the need for light weight structures and those with spatial constraints.

DfRem as in many other DfX requirements has to be designed into products and assemblies. This paper focuses on the embodiment design phase, in order to depict how remanufacturing design principles and practices contributes towards the enhancement of reliability and safety in product and assemblies for use during their extended life cycles. The embodiment design phase is where details on the form, functionality and performance are incorporated into a product or assembly.

Embodiment design as described by Dieter & Schmidt (2013) comprised three important design activities namely the architecture, configuration and parametric design. Design decisions at each of these activities are generally overlapping and has a large impact on the output of each design activity, more so when several design requirements have to be considered concurrently. Table 1 shows the activities in an embodiment design phase, the related design requirements for reliability, safety and sustainability under each design phase and how remanufacturing contributes towards reliability and safety during products' extended life cycle.

Table 1. DfRem as an enabler for ensuring reliability and safety at the Embodiment Design Stage.

Activities of the Embodiment Design phase (Dieter & Schmidt 2013)	**How incorporation of DfRem at the Embodiment Design phase enhances reliability and safety for life cycle extension**
Design Architecture **Arrangement of physical elements, Modularity** At this stage, functional analysis (using the black box model) provides an understanding on how product operates by analysing the material, energy and information/signal required to deliver all the functions/ sub-functions of the product. Moreover, the functional analysis helps to produce the architecture and rough	With remanufacturing as a life cycle thinking strategy, designers should be able to utilise the functional analysis tool to model the extended life cycle, focusing on material, energy and signal during the extended life cycle in order to take into consideration the cradle-to-cradle and close loop representation of the product life cycle.

geometric layout of the product/assemblies showing the architecture of the product.	With an accurate model representing the extended life cycle, aspects on reliability and safety with respect to material, energy and signal will be captured. Modular design are favourable for ensuring reliability and safety during the product useful life since this design architecture minimises design complexity and facilitates accessibility, part replacement and maintenance.
Configuration Design **Preliminary selection of materials and manufacturing processes, Modelling, Sizing of parts** At this stage, decisions on forms or morphology, material, production, and assembly must comply with the product functionality.	With DfRem, reliability and safety in the extended life cycle will be ascertained through: Selection of durable materials for identified cores Selection of reliable and standard parts to ensure availability Arrangements parts and components to support disassembly, and reassembly efficiency Arrangements of parts and components to facilitate inspection and cleaning. Avoidance of design and geometric complexity to facilitate repair and restoration Selection of fasteners that are not only durable but also do not damage parts and structures during disassembly and reassembly process.
Parametric Design Setting values for the design variables that will produce the best possible design considering both performance and manufacturability, includes Robust Design, DfX, Tolerances	With DfRem, reliability and safety in the extended life cycle will be ascertained through: Design for Disassembly that allow parts to be taken apart efficiently and inspected to ascertain their condition Design for ease of cleaning reusable cores. Design for Restoration to allow parts material and geometry to be easily repaired and restored to \`as new condition\`, Design for ease of inspection and testing, enables the quality and performance of the remanufactured products and assemblies be verified to at least its original specification, after which a warranty will be issued.

	Identify test methods and prediction methods to ascertain the reliability and useful life of the product during their extended life cycle.

The Way Forward for a Sustainable Design of Marine Components

Ships are defined as large, complex vehicles which must be self-sustaining in their environment for long periods with a high degree of reliability (Ship Design and Construction 2011). Equasis Statistics (2014) revealed that for very large ships (gross tonnage 60.000 and above), 50.3% are 5-14 years old and 13.7% are 15-24 years old. The study has also shown that for large ships (gross tonnage between 25.000 to 60.000), 48.8% are 5-14 years old and 16.5% are 15-24 years old. A majority of these ships will be reaching EoL in the very near future and this requires an efficient management of an environmental friendly recovery of marine components, assemblies and structures. EMSA (date unknown) noted that the shipping sector need to become more sustainable towards the long term objective of zero waste and zero emission.

The main parts of the ship which are the hull and the machinery, comprises several components and sub-assemblies such as the main engines and auxiliary machinery such as boilers, generators, machinery for manoeuvring, steering, mooring etc. These sub-assemblies comprised several cores that can be recovered for multiple life cycles if they are designed for remanufacturing, reliability and safety in mind. ERN (2017) highlighted the need to promote products suitable for remanufacturing. Today in the UK, some independent remanufacturers have been reported to conduct remanufacturing on marine equipment and components such as marine engines, propeller shafts, stern seals, rudder stocks, stabiliser stocks, Z-type drives.

Decisions related to remanufacturability, reliability and safety at the configuration and parametric design stage are large influenced by the durability of the materials, geometry, design architecture, design complexity and reliability of components and assemblies. Many design for X requirements have been established in the past, however, some of the requirements in the form of rules and guidelines may conflict with established DfX principles and actual design practices in the marine industry. Ability to predict the useful life of these cores during the design and development stage is now an area of growing interest as it will help to further ascertain the reliability and safety of the product or assemblies during their multiple life cycles.

This paper focuses on how DfRem helps to enhance Reliability and Safety in the marine industry. The industry, as in other transport industry namely aerospace, automotive and rail have high industry standards and specifications related to safety and reliability. Without a clear understanding on how remanufacturing contributes to safe, reliable and environmentally sustainable marine components and assemblies, remanufacturing as the most resource efficient EoL strategy could not be realised in the marine industry. Redesigning to facilitate remanufacturing is a challenging task due to limited data on design failures hence the need to acquire expert knowledge in the field. Designers and remanufacturers have to be engaged in developing products suitable for remanufacturing (ERN 2017).

Therefore, core/product remanufacturability will require data and knowledge of its environmental service conditions, physics of failure, potential failure modes and effects, the remaining life of the products etc. From data on failure modes and effect, repair and restorations can be clearly identified. With these data and knowledge, reliability and safety of cores/product can be predicted and ascertained. As it is a challenging task to acquire failure data, designers need to Due to difficulties in getting failure data on Therefore, an outlook for future study of design for remanufacturing in the marine industry in order to enhance life cycle extensions will need to include the following areas:

- The extreme environmental conditions that marine components and assemblies are subjected to during their useful life including analysis and quantification.
- The failure modes, frequency and effects of failure in marine components and structures.
- Configuration design of marine components affecting ease of inspection, disassembly and reassembly.

- Type of repair, restorations and testing of marine components during maintenance and restoration.
- Joining and fasteners used in the design and its impact on disassembly efficiency.
- Standards and specifications on marine component reliability and safety.
- Reliability analysis and prediction of products and assemblies in multiple life cycles.
- Life cycle impact of the remanufacturing process.

CONCLUSION

This paper provides a review on remanufacturing in general and how remanufacturing can be effectively implemented in the marine industry through the incorporation of DfRem. A review on the literature related to marine remanufacturing has shown that its implementation is rather low despite the high potential of the industry in contributing towards a more resource efficient economy via remanufacturing. In order to ensure effective remanufacturing in the marine industry, products and assemblies have to be designed to facilitate remanufacturing whilst ensuring that reliability and safety are not compromised in the subsequent life cycles of the products and assemblies. The review has proven the significant role of remanufacturing in ascertaining reliability and safety in the extended life cycle. However, due to the nature and service environmental conditions of marine components and assemblies, it will necessary to analyse the physics of failure, useful life prediction, configuration and parametric design requirements to ensure that remanufacturing is well integrated into this safety-critical industry. Design for Remanufacturing requirements are quite well established however they may be conflicting with general design rules and design practices in the marine industry. As such, design requirements have to be analysed and trade-offs be determined to ensure an environmentally sustainable design of marine components and assemblies for the circular economy.

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