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Sustainable polymer composite marine structures: Developments and challenges

Baley Christophe [1], Davies Peter [2, *], Troalen Wilfried [1], Chamley Alexandre [1, 2, 3],
Dinham-Price Imogen [4], Marchandise Adrien [5], Keryvin Vincent [1]

[1] Université Bretagne-Sud, IRDL, CNRS UMR 6027, BP 92116, Lorient CEDEX 56321, France
[2] IFREMER, Centre de Bretagne, Marine Structures Laboratory, BP70, 29280 Plouzané, France
[3] THALES, Centre de Brest, 29200 Brest, France
[4] IMOCA Class, 56100 Lorient, France
[5] Avel Robotics, F-56100 Lorient, France

* Corresponding author : Peter Davies, email address : peter.davies@ifremer.fr

Abstract :

The marine industry has been a major user of polymer composites for over 50 years. There has been a strong historical preference for glass fibre reinforced thermoset polymers, mainly polyesters and epoxies, but manufacturers are starting to realize that the current materials and practices are not sustainable. As a result, there is increasing interest in alternative materials, which offer the prospects of lower carbon footprints, reduced environmental impacts or both. The design decisions made today are critical, as many marine structures are designed for 20 to 30 years lifetime. In order to focus on viable solutions, it is essential to base these decisions on a balanced overview of the many new materials and processes. This review provides an up-to-date evaluation of emerging material options, fibres, matrix polymers and sandwich core and associated manufacturing developments. First, materials for the pleasure boat industry are discussed. Then high performance carbon fibre composite applications are described. These are discussed with respect to end of life scenarios such as re-use and recycling, life cycle assessment is examined. Recent examples of changes in material selection philosophy and associated benefits for sustainability illustrate what is possible and what remains to be done.

Keywords : Naval construction, New fibre reinforcements, New matrix options, Life Cycle Assessment, Recycling, Eco-design

1. Introduction

Composite materials are used throughout the maritime industry for a range of applications such as boat hulls and superstructures (civil or military), sterngear (propellers and rudders), offshore wind and tidal turbine blades, and underwater structures. Compared to other industries marine structures have some particular features. First, they can be very thick with large dimensions. For example, the main mast of a sailing boat may be 90 meters long, while floating wind turbines blades are currently around 115 and targeting 140 meters. Many marine structures are prototypes and this places additional constraints on costs, especially for tooling. These structures are used in a severe environment and may be heavily loaded. The consequences of climate change and loss of biodiversity are today widely accepted [1]. This has led to the introduction of notions of sustainability into all areas of construction. The maritime sector is a significant contributor to greenhouse gas emissions, 3% of the global total [2], with an objective for international shipping to reduce emissions by at least 20 per cent, aiming for 30 per cent by 2030, compared to 2008. Composites are widely used today for small vessels but could be used more extensively in larger commercial ships. This was investigated in two recent European projects, RAMSSES [3] and FIBRESHIP [4] and the Bureau Veritas now has certification rules for composite hull lengths up to 90 meters [5]. The drive to reduce emissions and develop a more sustainable industry requires up-to-date information on alternative materials options. This is the aim of the present review paper, which will examine these notions with respect to the manufacture of marine structures from polymer matrix composite materials.

The review is organized in four main sections. First, the application of the concept of sustainability to material selection will be defined. Then traditional boat and ship construction using glass fibre reinforcement will be discussed, in order to establish the baseline for the majority of marine composite use today. This is followed by a section discussing current and developing use of carbon fibre reinforcements in high performance marine structures. The various options for reducing environmental impacts will then be described.

2. Sustainability and material selection methodology

2.1. Sustainability

All human activities affect the environment and the concept of sustainable development is a major challenge for the 21st century. This idea was made popular by the Brundtland report (named after the president of the UN Environment and Development Commission) in 1987 [6]. The commission defined the concept as “development which meets the needs of the present without compromising the ability of future generations to meet their own needs’. The report of that Commission, “Our Common Future” has become the guideline for sustainable development today. Two important ideas are underlined:

- The concept of “needs’, and particularly the essential needs of the poorest members of society who should be a priority, and
- The idea of limits, that the state of our technology and our social organization impose on the capacity of the environment to respond to those needs, both now and in the future.

Sustainability is an ecological concept that expresses the capacity of a system to remain diversified and productive over a very long period. Sustainable does also require technical compliance with the product design specification, and includes environmental, social and governance (ESG).

Each of these aspects involves different problems and it is not possible to define sustainability only as a global property. Nevertheless, the economic and environmental aspects can be treated globally, as they have a planetary dimension, while social and cultural aspects are more influenced by local differences. The latter are not included in this review. While the idea of sustainable development appears to be a stable and operational concept, strongly supported by companies, politicians, and associations, in practice, it is quite controversial due to two interpretations [Figure 1]:

- Strong sustainability, which requires zero or even negative growth in order to preserve the environment
- Weak sustainability, which relies on technological progress to compensate for lost natural resources.

Figure 1

These two interpretations can be found in material developments. Strong sustainability can be illustrated by the development of biocomposites (polymers reinforced by natural fibres with reduced environmental impact). Weak sustainability involves pursuing the development of high-performance materials regardless of their current impact and assuming that future technology developments will repair environmental damage. These approaches are discussed further below.

Sustainability is also a subject of debate for economists. Some consider that the common indicators, growth rate and GDP (Gross Domestic Product) are poor choices and divert attention from the real challenges instead of helping us to address them [7]. One proposal is therefore to consider that economic activity should target human well-being, resilience and durability of society. Resilience is then defined as the capacity of a community, a nation or a biosphere to resist economic, social or environmental impacts. Sustainability should then aim to achieve well-being both faced with impacts and during normal conditions. The aim is therefore economic development contained within the physical limits of nature, designated in the scientific literature as “planetary limits” [8].

2.2. Specific aspects of composites for marine use

The useful lifetime of composite ships can be very long. A good example of this is the minesweeper class vessels (e.g. HMS Wilton, 46.3 m long; 450 tonnes displacement, with a monolithic glass reinforced polyester hull) [9]. For this application, R & D work started in the 1960’s. The initial lifetime was 30 years, but some vessels of this type are still in service, after 45 years.

In order to maintain these vessels at sea, factors to be considered include the complex loading (a ship operates at the air/water interface and even in peace time can undergo high local pressures (wave slamming and impacts with floating objects), the materials will absorb water at different temperatures and be exposed to UV radiation. Biological fouling will attach to immersed areas and coupling occurs between environmental and mechanical loading. Exposed appendices such as foils and propellers can also be subjected to cavitation. Figure 2 presents the parameters to be considered in boat hull material selection.

Figure 2

The use of composite materials in ships, just as in aircraft, benefits from their excellent specific properties (mechanical properties normalized by weight) to save weight [10]. This has knock-on effects [Figure 3]: Lower weight leads to smaller motors, lower fuel consumption, smaller fuel tanks, lower displacement and lower loads on the structure.

Figure 3

2.3. Recent developments in material selection methodology

Composite materials can be used in a wide range of marine structures with a large choice of constituents and technologies. In the 1980’s this choice was based on three criteria (Figure 4): required mechanical performance, production rates and acceptable material cost for the function.

Figure 4

The latter explains the difference between the aeronautical industry and naval construction (this will be developed in more detail below). Today eco-design is a fourth criterion which must be considered (accounting for environmental impacts of the complete life cycle), as defined in the standard [11]. This criterion is directly linked to sustainability.

It is also possible to consider a hierarchical procedure on two levels and to extend the selection criteria as shown below in Figure 5 (inspired by [12]).

Figure 5

Defining the sustainability of naval structures is not a trivial exercise; the approach employed at the pre-project stage is to assess the environmental impacts at each step of the life cycle, with the following aims:

- Reduce waste at each step,
- Optimize the structure to avoid under- and over-dimensioning,
- Use the most appropriate technologies,
- Employ methods such as value analysis (analysis of real needs),
- Store CO_2 when possible, by using renewable materials for example,
- Apply continuous improvement procedures, to progressively improve structural performance,
- Use recycled materials when possible,
- Design the structure to be repairable, in order to prolong useful life. This imposes control and maintenance operations,
- Include ergonomic and safety concepts (protection) for personnel (in the material choice, manufacturing, service and end of life),
- Consider end of life from the design phase,
- Be aware of legislation (REACH for example [13]) and anticipate changes,
- Quantify environmental impacts through life cycle assessment (LCA). This involves the analysis of incoming and out-going flows. The former correspond to everything that contributes to the manufacture of the product, the latter to all aspects of pollution. Among the input flows, the raw materials and energy are quantified, while the out-going flows will include waste, emissions, rejected fluids etc.
- Collection of reliable data concerning these flows. This is a critical LCA step. Their complexity and interactions between them lead to uncertainty over the impact values so they are termed “potential” impacts. The ISO 14044 standard [14] defines the methodology for such an evaluation. It encourages harmonization of the approach, robustness and a formalized reporting (with a requirement for an independent review of comparative LCAs). LCA provides a tool to help decision-making, a means of

understanding complex environments, and a framework to evaluate alternative designs. The goals and scope of the analysis and the objectives must be defined initially (the functional unit). If all the steps of the life cycle are to be considered (from cradle to grave) then the end of life needs to be clearly identified; this will be discussed in more detail below (section 7.4).

Naval construction is a large field and ships are complex structures. Both academic researchers and industrial companies have realized that building them must take account not only of economic costs but also of social and environmental factors. Sustainability evaluation includes the three components and so indicators should include them all [15]. Published papers provide LCA results for ships [16,17] and examples of the use of these analyses at the pre-design phase [18]. It should also be noted that for ship design it is necessary to satisfy certification society rules, particularly with respect to new composite materials [17]. The aim of the present paper is not to analyse all the published studies of LCAs applied to the maritime industry. However, two examples will be given below which clarify the approach (without judging the methodology, perimeter or assumptions made).

Burman et al. [19] investigated the influence of the material choice for a fast patrol boat (24m long, maximum speed 33 knots) built in either aluminium alloy or composite materials (monolithic or sandwich structures reinforced by either glass or carbon fibres). The vessel would be used for 25 years professionally (1000 hours per year, of which 300h at 100%, 500h at 50% and 200h at 10%). The use of composites results in a reduction of the hull weight by up to 50% for a sandwich structure reinforced with carbon fibres (considered here as the optimum) and of the displacement under load by 19 %. Fuel consumption over 25 years was estimated to be 3900 tonnes for the aluminium hull and 3125 tonnes for the optimum carbon sandwich, a lifetime gain of 20%. These results highlight one way in which the adoption of high performance composites can assist directly in improving sustainability. However, the concept of sustainability includes several contributions in addition to saving energy, such as reducing CO_2, and end-of-life options such as recyclability and compostability. These can result in competing requirements and may involve compromise. For example, monolithic composite hull would have a higher fuel consumption than the sandwich (3160 tonnes) but would be easier to recycle than a sandwich structure; this point will be discussed in section 7.3.

In a second example, Cucinotta et al. [20] examined the influence of the manufacturing process (hand lay-up or vacuum infusion of a GRP sandwich) for an 18.7 m long motor vessel with a maximum speed of 33 knots. Infusion results in a weight gain of 25% of the structure but only 9% of the displacement. The proportion of the constituents changes with the process; infusion allows, by weight, 21% more glass fibres but 57% less resin. For the same service use the choice of infusion results in less raw materials and waste, 15% lower fuel costs (646 tonnes less over 25 years), and less hull material to recycle. This paper [20] also examines three different service life scenarios (200, 350 and 500 hours/year).

These two examples illustrate the significant consequences of material and process selection. Studies of this type are essential to provide the arguments to justify (or not) innovative designs. The present paper will discuss the options available in order to address the Objective 9 of the United Nations sustainable development goals [21]: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.

3. Recreational boats and working vessels in Glass Reinforced Plastic (GRP)

3.1. Historical background

The first composites with polymer matrix (and plant fibres) date from the start of the 20th century [22,23], and were used to produce boat components (for example cotton reinforced phenolic watertight glands and winch parts), but hull construction started 30 years later with the development of glass fibres. The following section provides a brief overview of composite boat development:

- Following the first prototypes in 1937, series production of monolithic composite boat hulls started in 1947, followed in 1949 by sandwich hulls [24,25] . At the UK boat show in 1955 only 4% of exhibits were in GRP, this figure had reached 80% in 1972. In France production yachts such as the *Goliff* series (Jouët boatyard, 6.5 m and 1.3 tonnes displacement) were made from 1962 and 997 were built between 1962 and 1967). Other examples are the *Arpège* (Chantier Dufour, 9.25m and

3.3 tonnes displacement) of which 1500 were built between 1967 and 1976, and the *Sangria* (Chantier Jeanneau, 7.60 m and 1.7 tonnes displacement) with 2156 examples between 1969 and 1982. In France there were 20 000 pleasure boats in 1959 and 697 000 in 1987. This success was mainly due to the low cost of GRP compared to wood, low maintenance, easier repair and the possibility to produce large numbers of complex shapes from a single mould. Some of these vessels are still sailing today.

- The first all-GRP patrol boats were built for the US Navy in the early 1960s, and were used on rivers in the Vietman War [9]. It was also at this time that the first fishing and service boats were built.
- The UK shipyard Vosper Thornycroft led the way in glass fibre-reinforced naval vessels with the 450 tonnes displacement HMS Wilton launched in January 1972 [26].

  They subsequently developed the Hunt class Mine Counter Measures Vessels (MCMV) at 725 tonnes displacement with HMS *Brecon* launched in June 1978 and commissioned in March 1980 [9]
- The Swedish Navy *Visby* class 600 tonnes displacement stealth corvettes were built by the Swedish company Karlskronavarvet with construction starting in 1996 and the first vessel launched in June 2000. The hull is of sandwich construction with carbon fibre/vinyl ester laminate skins over a PVC core [27]
- *Mirabella V*, the largest single-masted yacht in the world (now renamed *M5*), was launched in November 2003. This 765 tonnes (half load displacement) vessel, built by Vosper Thornycroft, has an overall length of 75 m (247 ft) and the mast height is 88.5 m [25]. The hull is reinforced with glass fibres and the mast with carbon fibres.

Hull lengths have increased steadily with time up to 80-90 m long all-composite naval ships [9], but the trend stopped in the 2000s. This can be explained by the fact that for longer hulls the performance gain from the use of composites is less and there is generally no series effect. In addition, other criteria come into play such as the cost of moulds and materials (as soon as carbon fibres are used to provide the ship's beam stiffness), the difficulty of making a ship in sections and then assembling them in shipyard conditions, the difficulty of automating the manufacture of large parts, and concerns over the end of life. In comparison, the length of composite wind turbine blades continues to progress over time, but this is a structure without any real competition from other materials [28].

Concerning production methods, in the middle of the 1960s hand lay-up was the standard; polyester resins were used to impregnate mat and woven roving fibreglass [29]. From the 1970s, sandwich construction became more popular. Alternative resins such as vinyl ester and epoxy were also being used by the end of the 1970s. The growing market required faster production so more advanced fabrication techniques developed, and from the beginning of the 1980s, alternative reinforcement materials such as aramid, Kevlar and carbon fibres found a place in the industry [30,31].

In 1960, Owens-Corning Fiberglass Company sponsored a company (naval architects and marine engineers) to develop a reference book on the use of composite materials in boat building [32]. This book, still very useful for the design and definition phases of laminates, covers the following topics: Materials, boat hull design, design details, moulding methods, engineering properties of laminates and design of laminates. For the manufacture of composites, it presents techniques (chapter 4) such as heat cure, contact moulding, bag moulding either under vacuum or under positive pressure, autoclave moulding, spray lay-up.

3.2. Consequences of industrial production for end of life disposal of boats.

The development of series production of composite boats from the 1960's explains the large volume of aging vessels reaching their end of life today (Figure 6), which is a major concern.

Figure 6

In the past, there were wooden boat graveyards. Old hulls were beached in estuaries and the wood degraded naturally over time. There was a certain peacefulness in these places (Figure 7) but they were a source of pollution.

Figure 7

The wood was painted and many other materials were used. With composite materials, the situation is even less acceptable. Composite boat abandon is a growing problem on the estuarine foreshore [33,34] .

Various items and materials are observed within and around boats. These include tyres, timber, plastics, electronic equipment, canisters and metal objects. Abandoned composite boats contain pollutants (e.g. plastics, heavy metals, oil related hydrocarbons, anti-fouling paints based on now illegal tin products) and represent a hazard to humans and wildlife.

Because composite vessels are highly durable, end-of-life disposal has not so far been a major issue.

The waste management hierarchy ranks options from least favoured to preferential as follows: energy recovery / recycling / reuse / reducing the amount of waste and prevention [Figure 8] [35].

Figure 8

The production of boats in large numbers over the last 50 years requires a strategy today to deal with their disposal. The current context includes:

- An increase in regulatory pressure on the end of life of consumer products;
- The need to include end of life of composite components, through the development of new materials, new manufacturing procedures and improved design;
- The desire of industrial companies to show that their activity is part of the circular economy and to minimize negative images of the production and use of their products;
- The need to reduce waste. The action plan of the Green Pact for a Circular Economy aims for less waste, and the French roadmap for a circular economy (FREC) [36] imposes a reduction of waste by 50% in 2025 compared to 2010.

Today in France, pleasure boat production generates 14% factory waste. This is made of glass fibres (22%), of resin (mainly thermoset polyester) and gel coat (19%, a thermoset matrix, additives and fillers that degrade itself in water) and of composites (59%). One logical step is to replace the thermoset matrix resins with either recyclable thermoset resins or thermoplastics, re-usable through thermo-mechanical processes, and to develop new manufacturing methods. These are discussed in section 3.3 below.

For boats reaching their end of life today the main difficulties in recovering materials for re-use are:

- The presence of multiple materials, adhesively bonded or otherwise assembled together (foam cores, wood, inserts …);
- The absence of information on the exact nature of the composites, due to a lack of traceability.

In France the APER (Association pour une Plaisance Eco-Responsable) [37] was set up by the Nautical industry federation (FIN, Fédération des Industries Nautiques française) to develop an industrial sector devoted to boat deconstruction. The APER is an eco-organization, certified by the Ministry for the Ecological Transition to manage the dismantling of old boats and recycle as much as possible. It is the first of its kind and is based on the principle of producer responsibility. This principle, which exists in France since 1975, (article L. 541-10 of the code for the environment), obliges producers, importers and distributers to contribute to waste elimination of their products. A network of boat collection centres was set up and there are around 30 throughout France today.

The boats currently collected contain a high proportion of composites (68 %). In 2020, the composite waste was mainly (63%) directed towards energy recovery through incineration. There is no re-use nor recycling of the composites from the pleasure boat industry. This can be partly explained by the low cost of glass fibres and the lack of cheap technology to recover them. In 2020 the deconstructed boats were on average 40 years old [38] against a design life of 25 years.

It should also be remembered that production boats require moulds. The manufacture of a mould produces waste, requiring an initial form, which is usually employed once then discarded, and the end of life of the mould itself should also be included in an LCA.

3.3. Options to improve future recyclability of matrix polymers

In order to recycle boat hulls in the future there are two main options; either develop recyclable thermoset polymers or switch to thermoplastics which are recyclable. However, this may result in significant reductions in performance parameters.

3.3.1 Recyclable epoxy resins

Considerable efforts were made in the 1990's to reduce the environmental impact of thermoset resins with the development of various grades of "green epoxy". For example, *Sicomin* offers a range of products with different biobased components (up to 56%), with improved LCA [39]. However, this does not affect end-of-life as these resins cannot be recycled. In recent years, developments in resin chemistry have provided epoxy and unsaturated polyester formulations that are recyclable [32]. This has been achieved by focussing on hardener/catalyst chemistry, so that even after cure the three-dimensional molecular network can be broken down using mild solvents. The best-known example is the *Recyclamine*™ technology developed by Connora in 2012 and now owned by Aditya Birla [40,41]. These recyclable resins can be processed using existing technology such as infusion, so boatyards do not need to invest in new equipment. There are few results available describing composite properties with these resins after marine ageing [36], but work on carbon fibre reinforced Recyclamine™ epoxies at Ifremer has shown residual properties similar to those of standard marine composites after extended (12 month) seawater aging [42]. La Rosa et al have published LCA results for Recyclamine™ hardener epoxy resins, before and after recycling [43] and these will be discussed in section 4.8 below.

It is interesting to note that manufacturers of large composite wind turbine blades have recently started to use these resins in order to improve the environmental impact of their turbine structures [44] and more widespread marine applications are likely.

3.3.2 Self-healing polymers

During service damage can initiate in composites (matrix cracks, interface debonding or even fibre breakage) and propagate leading to a risk of structural failure. Natural composite structures such as trees use self-healing mechanisms to repair themselves and have inspired material developments to imitate this. Two elements are essential, the capacity to supply repair products in-situ and the need for a durable repair [45].

Over the last 20 years several self-healing concepts have been developed. While these are not yet used in naval construction their potential to extend the service life of highly loaded parts such as foils make them an interesting material option for improved sustainability.

These materials may or may not be autonomous [46–48]. For the former there is no need for external stimulation to repair damage (automatic healing without triggering). For the second, non-automatic healing with triggering) a stimulus such as heat, mechanical stress, chemical, light, radiation, or magnetic field is required to initiate repair.

Another possible classification is between single use repair materials, hollow fibres for example [49], and multiple use such as vitrimers [50]. In all cases it is the composite matrix and/or the fibre/matrix interface which is repaired, not the fibre reinforcement.

Examples of the benefits of self-healing composites have been shown for fatigue properties [51], delamination [52], interfacial bonding [53] and flexural properties after impact [54]. In general the lifetime extension resulting from damage healing provides improved sustainability.

Concerning the materials which can provide healing properties the most promising are based on vitrimer polymers [55]. First proposed by Leibler et al in the 1990's [56] these new polymer structures combine the mechanical properties of thermosets with the possibility to flow and repair. They may provide a future alternative to the recyclable epoxy matrix polymers described above, allowing healing, correction of moulding defects and recycling [50,57,58].

3.3.3 Thermoplastic matrix

The second way to facilitate recycling of marine composites is to adopt a thermoplastic matrix polymer. This requires a change in forming approach, as these polymers require elevated temperature and pressure in order to reduce their viscosity and impregnate fibre reinforcements. However, this change can improve working conditions (no contact with liquid resins, no volatile emissions) and the resulting composite can then be recycled by mechanically grinding and applying a new thermal forming cycle. The polymers available include polypropylene (PP), with a melting temperature (T_m) around 160°C, poly(lactic acid (PLA), a bio-sourced polymer (T_m 170°C) and various technical polymers such as polyamides (with improved properties but T_m around 220°C). The marine use of thermoplastic matrix composites was demonstrated several years ago. For example, a paper published in 2009 describes recycling issues associated with a 8.5m experimental rigid inflatable boat (RIB), manufactured in thermoplastic (glass reinforced polypropylene) composite to demonstrate the viability of thermoplastics technology in marine composites (60 wt% glass) [59]. The internal structure was a sandwich construction with a balsa core. The authors demonstrated the recyclability by melt processing into injection mouldable granules of thermoplastic-based composites. This type of technique has also been studied for the development of a thermoplastic composite system for structural application in the chassis of an electric bus [60].

Another marine study in the NAVECOMAT project (2007–2011), resulted in the manufacture of a Flax/PLA canoe demonstrator (figure 9) [61].

Figure 9

In this case the thermoplastic matrix allows mechanical recycling, grinding followed by injection moulding, with biodegradation by composting at the end of life when further recycling is no longer possible. Marine aging studies of this composite were performed [62,63], as well as the quality of the fibre/matrix interface [64,65] recyclability [66] and the environmental impact benefits [67,68].

Most boat hulls are protected by external coatings, either gel-coats, a thin layer of resin placed on the mould surface, or paints. This operation is more difficult for thermoplastics due to the thermal cycle and low surface tensions of polymers such as PP. In the glass/PP study described above the hull surface was painted with an epoxy-based primer, followed by Standard Marine topcoat. Treatment with a primer is usually necessary when coating thermoplastics because of their non-polar nature that inhibits adhesion [59].

For the PLA/flax study (Figure 9) a thick PLA film was placed on the mould surface as the first layer [69].

Figure 10 shows a glass/PP catamaran currently produced in France and used intensively in sailing schools. The hulls are hot moulded from a woven glass and PP fibre mixture semi-product. The boat is supplied without any protective layer (no gel-coat nor paint), which simplifies recycling.

Figure 10

For the manufacture of large thermoplastic ship structures, heated presses are not appropriate and forming can be carried out at temperature under vacuum in an oven or in an autoclave if higher pressure is needed. An alternative may be AFP (Automated Fibre Placement), with laser heating for example. This allows precise control of heating cycles, more critical for semi-crystalline polymers that crystallize on cooling. However, this requires robotic equipment and pre-impregnated tape and these are both expensive, so it is limited to high performance components today [70].

Various thermoplastic semi-products are available, as described by Wakeman et al. [71]; the polymer may be present in the form of powder, films, or fibres (mixed with glass or carbon fibres). Compression moulding was used to manufacture flax reinforced PP [52] under vacuum at 180°C from stacks of unidirectional plies with polymer films (film stacking) in [72].

Another marine application for which thermoplastic composites are being studied and which uses AFP manufacture is for drifting instrumentation pods to resist hydrostatic pressure for deep sea exploration, [73,74].

These autonomous floating profilers (see Figure 11) provide data on oceanographic parameters along the water column at depths to 2500 meters, as part of the global ocean observation project [73].

Figure 11

Over 3000 floats have been deployed to date. Current developments are extending these operations to 6000-meter depths, and carbon fibre composites are the preferred material. Thermoplastic composites have been studied for deep sea casings, and tests on both carbon/PEEK and carbon/PA6 have been described [75,76].

While these offer the possibility of recycling after recovery they do not provide a solution if the structure is lost at sea, and this aspect will be discussed in more detail in the following sections.

In order to make recycling easier a novel approach is to use self-reinforced (SR) thermoplastics, composed of thermoplastic matrix reinforced by the same polymer in the form of fibres. The concept dates from 1975 [77,78] but has been the subject of recent studies for marine structures [79].

While studies of SRPLA appear promising, the properties remain close to those of PLA. However, other combinations such as high modulus polyethylene fibres in a polyethylene matrix should provide significantly higher performance, provided fibre/matrix interfaces can be optimized [80].

3.4. Resin Transfer Moulding (RTM) of thermoplastic composites

The RTM technique, impregnating reinforcements under pressure, is often employed in the production of thermosetting matrix composites. A similar technique can be used in special cases for thermoplastic-based composites, when a part needs to be welded or recycled, or even when the part must undergo thermoforming processes [81]. To differentiate between the RTM technique used for thermoset resins and that used for thermoplastic resins, several authors have used the terms T-RTM or TP-RTM for thermoplastic RTM [82].

In contrast to thermosets there are only a few commercially available reactive thermoplastic systems suitable for in situ polymerization in the TP-RTM process, namely polyacrylate matrices (Elium®, Arkema), polyamides (Bruggolen®, Brüeggemann Chemical), and polybutylene terephthalates (Cyclics CBT®, Cyclics Corporation) [83]

Regarding academic research, the use of certain cyclic esters as monomers (such as ε-caprolactone and L-lactide [L-LA]) in the TP-RTM process has been studied, and has shown satisfactory results for the production of biodegradable matrix-based composite materials [82,84]. Other polymers being studied, include PA6 [85], and PA 12 [86].

The production of thermoplastic matrix composites by TP-RTM is attractive, resulting in good impregnation of the reinforcements, and the possibility of manufacturing large parts with some polymers (polyacrylate matrices for example). This explains the recent interest for making ship hulls or wind turbine blades [35,87–89].

The case of the Elium™ acrylic matrix, introduced in 2014 by Arkema, is attracting considerable interest in the marine industry. This is a liquid resin, which can be infused and then reacts to form a thermoplastic. It offers the possibility for boatyards to continue using existing forming technology but producing products which can be recycled. The recycling process of this polymer proposed by the manufacturer is based on a chemical method which involves depolymerization at elevated temperature (>300°C). The fibres can then be separated from the resin and a new polymer can be obtained. This method can be applied to both production waste and at the end of life of components. It is not the classical recycling used for polymers such as PP, Polyamide which is based on grinding and remoulding (injection, compression) at temperature. This latter approach has been tried with the Elium resin but in order to re-inject it was necessary to add a large proportion of virgin polymer [87].

With respect to durability for marine applications, an experimental study of the mechanical behaviour of glass and carbon reinforced acrylic composites showed similar property retention after seawater aging to marine epoxy composites [90]. There are few data available from LCA studies on this polymer and its composites at present.

3.5. 3 D printing of thermoplastic composites to manufacture moulds, tooling and small boats

Additive manufacturing is a widely used production method for prototypes and small components. For marine applications, studies at the University of Maine have shown that the technique can be used to produce boat forms for moulds [91], the moulds themselves [92] and even small boats [93] . This technology can save time; a complete 25-foot (7.27 m) long boat weighing 2500 kg was printed in 72 hours [93].

While 3D printing of filaments containing short fibres does not provide adequate mechanical properties for structural parts, printing continuous fibre reinforced filaments can result in good properties and complex shapes [94,95]. This process can enable optimization of fibre orientations, around holes for example [96]. The process is complex, requiring control of fibre impregnation, fibre content and porosity, bonding between layers and residual stresses. The application of compacting pressure either during filament placement or by a post-treatment will improve properties [97]. Further developments such as so-called "4D printed" continuous fibre reinforced composites offer the potential to incorporate additional sensing and actuation functions, opening up the possibility for the development of smart load bearing printed structures [95].

3.6. Boat hull assembly by welding thermoplastic plates

The difficulties in recycling composites have led some boat-builders to propose motor boat hulls (up to 12 m long) out of thermoplastic (high density polyethylene, HDPE), assembled by welding plates together. The technology is based on boiler-making techniques such as those used to make plastic tanks for the chemical industry. These boats are proposed for both professional and pleasure use. The boat-builders promote sustainability advantages such as recyclability of HDPE, and no need for anti-fouling paints. Indeed micro-organisms do not stick to HDPE easily, though regular hull cleaning 3 or 4 times a year is recommended as biofilms can still adhere to these materials [98].

3.7. Reduced impact sandwich cores

As noted in section 2.3 sandwich construction has been extensively used for marine structures. In addition to options for monolithic composites which are used for sandwich facings, innovative core materials can also provide potential for more virtuous structures. Cores are mainly of two types, foams and honeycomb [99]. One approach is to replace the widely-used PVC (polyvinyl chloride), which may be linear or cross-linked, with a PET (polyethylene terephthalate) foam. The latter can be recycled and can also be produced from recycled PET [100,101].

Several recent projects have characterized PET foams. For an equivalent density their properties are lower than those of PVC but can provide an acceptable alternative in boat structures [102]. Some LCA results are available for these products e.g. [103].

The best-known honeycomb core is the Nomex™ product range, based on resin-impregnated aramid paper. Various lower performance alternatives are available which offer improved end of life possibilities, including PP based honeycombs such as Nidaplast™ [104].

A third alternative is to use natural bio-sourced core materials. The best-known of these is balsa wood, which has been used for many years in marine sandwich structures [105]. Another option is cork [106]. Both these materials are heavier than the foam equivalents and more sensitive to moisture but their biosourced nature can be favourable for their carbon footprint.

4. High performance naval structures / racing yachts

4.1. Introduction

There are currently two distinct development objectives for the use of high-performance carbon fibre reinforced composites in marine structures:

- To increase the performance, i.e. the ratio speed/displacement. This is the case for racing yachts.
- To apply these materials to large commercial ships using wind power, to reduce their energy consumption. In this case the weight of mast structures must be optimized, to satisfy stability criteria.

In both cases the choice of materials, manufacturing technology and end of life management must be addressed. It is interesting to note that for many years boatyards have developed materials and processes which are specific to nautical construction. There were therefore significant differences compared to aeronautical structures, but there have been examples where aeronautical materials have been adopted. In the mid 1980’s a new generation of military submarines was initiated (SNA, nuclear attack submarines) and the outer decks used 120°C cure pre-impregnated reinforcements. Given the very large surface area and volume of composites cost reduction was a major factor. Another example is the use of 180°C cure carbon/epoxy prepreg composite propellers for landing craft [107].

However, for racing yachts the need for performance at all costs took a different direction, and gains have been made in reducing weight and increasing speed by design optimization (architecture, hydrodynamics, aerodynamics, numerical calculations). The use of foils is an example, leading to a large reduction in the vessels” hydrodynamic resistance. These appendices are constantly improving, some now integrate sensors to measure loads during navigation. Provided they are authorized by class rules (the yacht categories impose gauge rules) the composites used are mainly carbon/epoxy prepreg either hand laid or using AFP, cured at 120°C (the maximum temperature allowed by the rules) in an oven (hull, deck, bulkheads) or an autoclave (mast, boom, foils). Some parts are also made by infusion. To give an order of magnitude the cost per kg of hull is around 1000 euros. Today the use of LCA to evaluate environmental impacts is revealing the limits of the race for performance at any cost, and the industry is starting to ask questions on its future. This will be illustrated by the case of foil manufacture.

4.2. Foils and load-bearing surfaces

4.2.1. Context

This section is devoted to high performance marine structures. These are complex systems which are subject to many optimization steps and technical developments. They are also an example that is being increasingly studied in order to quantify and reduce environmental impacts. The sustainability of such structures is not simple, as the quest for performance at all cost results in continuous technological innovations, leading to the construction of new vessels whose lifetimes are very short. The end of life solutions for these boats are very limited. By way of example we will first discuss in detail the manufacture of racing yacht foils, then the complete vessels.

Load-bearing surfaces have various forms in marine applications, such as propeller blades, rudder blades, stabilizers, diving bars and more recently hydrofoils or foils. These structures generate and support hydrodynamic loads (lift, drag, thrust and torsion), the amplitudes of which can be very high. Their performance is usually limited by cavitation, ventilation, natural frequencies or a minimum thickness. The design of foils requires fluid/structure interaction studies, in order to predict the hydrodynamic and structural responses. Composites show significant advantages for this application compared to metals, in particular higher specific strength, the possibility to adapt the response by modifying fibre orientations and thickness, and better fatigue behaviour. The improved performance of sailing vessels with foils has been clearly demonstrated for many years, but more widespread use was slow due to the need for high performance materials. With more extensive marine use of carbon fibre reinforced composites this restriction was removed and they are now proposed for a range of marine structures, from kite-surf boards to large multi-hulls.

4.2.2. Example: foils on 60-foot racing yachts

Over the last 10 years the use of foils in yacht racing has extended from regattas (America Cup, AC50, AC75 classes...) to ocean racing (IMOCA, Ultim classes…) on monohulls and multi-hulls. Here we will concentrate on the IMOCA class. These 60-foot yachts are designed for single-handed round the world races (the Vendee Globe). This requires an efficient, robust yacht, which can adapt to meteorological conditions around the world. The performance of these vessels has progressed significantly since 2002. Since then they have integrated canting keels and then foils, in 2016, which have continued to develop along with the hull architecture. This has resulted in a remarkable 50% overall increase in sailing speeds.

Foils on sailing boats (Figure 12) have two functions:

- Reduce hydrodynamic loads on the hull to reduce drag effects, and
- Balance the loads on the boat by generating a hydrodynamic force to oppose aerodynamic loads on the sails.

These are prototypes with a complex non-symmetrical geometry, with an overall developed length of around 7.5 m, a maximum surface area of 7.7 m² ([108], see section 4.7) and weigh around 300kg. The cost of a foil is between 200 k and 300 k euros.

An example of the use of foils during navigation is shown in [109].

Figure 12

Figure 11 shows the working principle of a yacht with foils under sail, the keel and foils are mobile. There are two design loading cases:

- Bending of the foil due to hydrodynamic loads generating normal stresses in the zone close to the hull (Figure 13.a). The axial compression strength (Xc) of these structures is often their weak point. The shear stiffness of unidirectional plies, dependent on the matrix resin, controls the compression strength of continuous fibre composites [110]. In this application more than 80% of the plies are oriented along the foil axis, which is a significant difference compared to composite structures in other sectors such as aeronautical where quasi-isotropic materials are very common.
- A second loading case (Figure 13.b) corresponds to reverse bending, where the loading direction is reversed, which generates out-of-plane transverse tensions in the foil at the curved “elbow” (Figure 13.b). When the foil is produced by 2-D lamination the delamination resistance is then critical (Interlaminar transverse strength: ILTS). Instrumentation with optical fibres has shown that this loading case occurs regularly and this has led to the development of foils with 3-D reinforcement (termed 3D in the following sections).

Figure 13

4.2.3. Manufacture of foils with 2D or 3D reinforcement

The first foils were laid up flat (2D) and delaminations appeared during testing. To overcome this, one solution was to integrate metallic inserts, (Figure 14), but the interfaces between metal and composite then posed additional problems.

Figure 14

Around 2017, alternative methods of fabrication using AFP, Automated Fibre Placement, [111] used in the aircraft industry, were evaluated to improve quality and reliability compared to the traditional method (manual lay-up with curing under vacuum or infusion). The results showed improved performance in terms of delamination resistance (ILTS), [112] and compression strength [113]. The AFP robots developed for the aeronautical industry by *Coriolis Composites* (Queven, France) [114] were employed, the aim being to benefit from their capacity for additive manufacturing.

The material used by the AFP robots is an impregnated ribbon (carbon/epoxy) of width around 6 mm (1/4 inch). This narrow width allows them to be deformed during placement to form complex shapes. For aeronautical structures published studies have examined the influence of steering (radius of curvature during placement) on mechanical properties [115], and a minimum radius of 1500 mm is recommended to avoid local misalignment of fibres and a loss of properties. This radius is compatible with foil geometries.

Foils with a planar lay-up (2D) represent only 20% of IMOCA foils made today. They can be produced by an AFP robot or by hand lay-up. In both cases they require moulds. If the mould is applied to the outer face, an extra thickness of around 10% of the total weight of the foil is added, which is then machined off to produce the inner surface. The moulds weigh around 800 kg for the production of components of 600 kg (Figure 15. a). Manufacture of the moulds has a significant environmental impact and must be included in the LCA. They are usually in carbon/epoxy, in order to have a similar thermal expansion coefficient to the component during cure, but are difficult to recycle after use. Steel moulds (Figure 15.b), are easier to recycle and have been tested, but this makes cure cycles more complex and requires additional machining. If the mould is a “ski slope’, where only the foil outline is given, (Figure 15.c), then machining of both surfaces is necessary and the extra thickness can reach 25% with a significant increase in material waste.

Figure 15

To reduce the risk of delamination a process has been developed which enables fibres to be oriented in 3 directions. This 3D structure represents 80% of the foils produced today. The technique involves manufacture of battens, then assembly by bonding and machining to make the foil (Figure 16). After machining additional layers are added to the outer surface to take the torsion loads. Optical fibres are often included to measure strains during navigation. This method does not require moulds, only a flat surface for lay-up, which reduces the environmental impacts.

Figure 16

The battens can also be machined from plates produced by manual layup or AFP (Figure 15.d). The latter allows the fibres to be placed following the batten geometry (following the profile curvature and optimizing local trajectories) which leads to an improved structure. Details of foil fabrication can be found in [116].

4.2.4. Greenhouse gas generation during foil manufacture

The use of LCA tools is becoming more widespread in the world of ocean racing yachts. This is leading to a re-evaluation of certain practices and rules, together with a certain apprehension of the imposition of sustainability criteria. The pleasure boat industry is also affected [117–119].

The aim of the following section is to provide some elements on which to reflect with respect to future orientations, using foil manufacture as an example. Two aspects will be considered in a simplified approach; primary energy consumption and equivalent CO_2eq. emissions. Equivalent CO_2 is a value which allows the main greenhouse gas emissions to be quantified. In order to account for CO_2, methane, nitrous oxides, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluorides the five latter are converted to a global equivalent CO_2.

LCA requires robust and accessible data, which can be verified by independent evaluators, but this is not always possible for commercial processes. This is understandable when the process is confidential and the market is competitive. For example, several authors have compared literature data for the production of 1 kg of carbon fibres [120,121] (fabrication of the precursor then conversion to fibres). The amount of primary energy required varies by a factor of 1 to 10. Dér et al. [122] indicate a high value; they estimate that the energy intensity of the investigated carbon fibre production line amounts to 1150 MJ/ kg carbon fibre).

In order to verify this figure, it would be necessary to know details of the type of fibre produced, all the production steps and the industrial capacity. Kaur et al. [123] showed that the quality of the precursor has a strong influence on the properties, the production efficiency and the cost of production. The capacity of the industrial equipment will influence the energy consumption [121].

Foils use different types of carbon fibres, referred to as SM (Standard Modulus) / Modulus 230 to 280 GPa, also often referred to as High Strength (HS), IM (intermediate modulus - modulus 280 to 340 GPa) and HM (high modulus - modulus >340 GPa). These require more or less elevated temperature cycles (heat treatment temperature around 1500 °C for SM, and above 2000 °C for IM and HM [124].

In the absence of exact data, we will adopt mean values here: Ghosh et al. [120] estimated the primary energy required to produce 1 kg of carbon fibres (SM *a priori*) at 460.7 MJ/kg and greenhouse gas emissions at 30.1kg equivalent CO_2. The conversion of the precursor to fibres represents 35% of the energy and 37% of the CO_2 emissions.

Table 1 shows an estimation of the total energy and the CO_2 emissions (from literature values and measured data) to produce 1kg of carbon SM/epoxy composite with a fibre content by weight of 66 %. The energy consumption was measured by *Avel Robotic* (France) for the AFP process and an autoclave cure. Fibre manufacture is the main contributor to CO_2 emissions (80%), estimated at 24.9 $kgCO_2$ equivalent for 1 kg of composite.

Table 1: Estimation of the energy requirement and equivalent CO_2 emissions in the production of 1 kg of composites (weight fraction 66%).

Production of 1kg of carbon SM/epoxy composite	Data source	Primary energy MJ (1)	DEC (kWh) (2)	Conversion Coefficient kWh => $kgCO_2eq$ (3)	$kgCO_2eq$ (4)
340g of epoxy resin	[125]	26.5	7.4	0.08	0.6

660 g of SM carbon fibres	[120]	304			19.9
Manufacture of 1kg of prepreg	[126]	40	11.1	0.08	0.9
AFP robot placement	Measured		17.8	0.08	1.4
Autoclave cure	Measured		7.1	0.08	0.6
Assembly/Workshop	Measured		6.4	0.08	0.5
Machining	Measured		12.8	0.08	1
Total					24.9

(1) Primary energy MJ/kg. i.e. 78 MJ/kg for 1kg of epoxy [125] and 461 MJ/kg for 1 kg of SM carbon fibres [120].

(2) DEC: Direct energy consumption. 1MJ = 0.2778 kWh

(3) The coefficient of conversion from KWh to equivalent CO_2 depends on the energy production route, which depends on the geographical location (country) and time of the year. For example 1 KWh of hydraulic energy produces 0.004 kgCO_2 whereas 1KW from coal produces around 1 kg of CO_2equiv. For France, which has an energy mix with a large nuclear component 1kWh produces 0.0801 kg of CO2equiv (i.e. 0.0801kg eq. CO_2/kWh). In Japan, the grid mix produces 0.535 kg eq. CO_2/kWh (https://base-empreinte.ademe.fr). The foils studied here are produced in France. We consider that the epoxy resin manufacture (produced only with electricity) and the fibre impregnation take place in France.

(4) The production of 1kg of carbon fibres produces 30.1 kg CO_2equiv [120].

Based on these figures we are now able to estimate the CO_2 emissions associated with the production of a pair of foils (around 300 kg each). These are prototypes, so, each 2D foil needs a mould (two per boat as they are not symmetrical) and machining (loss of material). For 3D foils the loss of material is higher but moulds are not required. The estimations here are based on real foils, which use SM, IM and HM carbon fibres. However, details of stacking sequences and thicknesses remain confidential.

Table 2 provides published data for the two foils [127] and the estimation for the foils manufactured by AFP at *Avel Robotics* (France). This enables greenhouse gas emissions to be estimated to show the influence of the structure (2D or 3D), the use of a mould and the mould material (steel or composite), the type of reinforcement and machining material waste. The calculations were performed using the *MarineShift 360™* software/ 2022 [128]. With this software the data for the different types of carbon fibre are not known so the results are estimations. Table 2 shows that the manufacture of foils has a high environmental impact. but that the emissions vary by a factor of 4 according to the process. Not using a mould and adopting a process which limits machining are favourable to reducing the impact.

In general two different sets of foils will be used on a boat in a 5 year period (aging and optimization) and the foil wells (the internal hull structure which supports the foil) are not included in the analysis. The final column in Table 2 shows the gas emissions per net kg of composite (total emission divided by the total quantity of composite transformed to produce 2 foils).

For the bottom line (fabrication of a 3D foil by AFP with a material loss by machining of 50%) the emission for 842 kg of composite (2 foils each 421 kg) represents 29.7 kg equivalent CO_2 per kg of composite, a value close to the one in the previous Table given that different types of carbon fibres (SM, IM and HM, see Figure 15) are used.

Data source	Type of structure	Fibre placement technique	Use of a mould	Main type of fibres used	Foil weight (Kg)	Total weight of composite transformed	CO_2 eq. emission for a pair	$KgCO_2$/Kg of foil net

						(1 foil + tooling)	of foils (1 boat)	
[127]	Plane (2D)	Manual	Yes, reinforced by SM carbon fibres	Carbon IM et HM	300	1575 Kg	96 T CO_2eq	160
Avel Robotics via MS360 - 2022	Plane (2D)	AFP	Yes, but steel mould 700Kg recyclable	Carbon IM and HM	283	418Kg	38 T CO_2 eq	67
[127]	Out of plane (3D)	Manual	no	Carbon IM	343	1272 Kg	103 T CO_2 eq	131
Avel Robotics via MS360-2022	Out of plane (3D)	AFP	no	Carbon IM	279	421 Kg	25 T CO_2 eq	45

Table 2: CO_2 equivalent emissions for manufacture of different foils versus their structures (2D or 3D), use of a mould, type of fibre placement, optimization of the process and total amount of composite transformed.

4.3. Construction of a racing yacht (60-foot IMOCA) and sustainability

Having examined the factors which affect the environmental impact of an appendix we will now examine the impact of the complete vessel which uses those foils.

The report by *11th hour* [127] estimates the amount of CO_2 equivalent emissions during the construction of a 60-foot IMOCA yacht in 2020 (from production of the material components to first navigation) to be 553 tonnes. Estimates for a yacht of the same class produced in 2010 were 343 tonnes [127]. The increase reflects the technological improvements and in particular the developments in the use of foils. In addition, navigation for 5 years will require a spar rudder, a set of sails, a second set of foils and rigging; an additional 116 Tonnes CO_2 equivalent. If we consider that the construction and optimization of the yacht represents only 25% of the total emissions of a sailing team over 5 years, (the hypothesis of [127]) then the total impact will be around 2670 to 3000 Tonnes of CO_2 equivalent. This is a very high impact for a sailing boat using wind (a renewable energy) to navigate. End-of-life management of the boat structure is not included in this figure.

By way of comparison. ADEME (the French agency for ecological transition) [129] estimates that the average individual annual carbon footprint of a French citizen was around 8 tonnes of CO_2 equivalent in 2022. An emission of 3000 tonnes thus represents around 375 years of emissions for an average French citizen. Barros examined the carbon footprints of very rich citizens at around 10 000 Tonnes CO_2eq per year [130], with 3 main sources: dwellings, transport, and yachts. Possession of a super-yacht represented between 70% and 80% of these emissions.

The construction of a racing yacht represents only around 25% (an estimation which varies according to the boat) of the emissions as there are many other sources such as equipment (electronics for example), maintenance and transport. For example, if a yacht returns after a transatlantic race by cargo ship (e.g from the West Indies to France), the equivalent CO_2 emissions are around 48 tonnes for a 40-foot yacht (Class40), 92 Tonnes for a 60 foot (IMOCA), and 235 tonnes for a multihull (39 to 59 feet in length).

As for any analysis of this type, the exact values employed in these calculations are open to discussion. Nevertheless the report on which they are based [127] is freely available and at least serves as a basis for debate. More important, it can also indicate areas of improvement, though there has not been any significant improvement in impact since 2020, despite the Paris agreement to reach carbon neutral status by 2050 [131].

By optimization of all the stages of the life cycle of boats it is possible to reduce their environmental impacts. This is illustrated by the example of foils, for which a reduction by a factor of 4 was shown in section 4.2.2. It is also possible to change the class rules to impose reductions (see section 4.7).

The quest for speed is not limited to racing yachts and technological developments have resulted in remarkable gains in performance, but the figures above pose a number of questions: Is this sustainable ? Is it socially acceptable? Will sponsors continue to consider racing yachts using renewable wind energy to be a clean sport? For the sailors, is the aim to go faster at all cost or to arrive first in a race on an equal footing? What does the public want to see?

Today there are excesses in many sports. This was analysed by Villepreux [132] who highlighted the role of the media in the recent development of sporting activities. There was a change at the end of the 1980's. It was no longer sufficient to comment on the quality of the game or the beauty of the action, as if commenting a play or a film, but also necessary to inform on the economic aspects. The use of sport for publicity increased significantly and sportsmen and women became symbols of positive values for society, showing the virtues of hard work, and surpassing oneself to achieve a goal. Sports became a complex interaction between sponsors and the media, resulting in excesses from which it is difficult to return. However, global conditions are changing and it is no longer possible to ignore the impact of such activities on climate change and biodiversity.

4.4. Transfer from racing yachts to maritime transport

The maritime transport industry must reduce its CO_2 emissions by 40% by 2030 and by 50% by 2050 [133], taking 2008 as the reference year, according to the International Maritime Organization (IMO) strategy. The aim is to develop wind-assisted ship propulsion technology in order to meet a carbon neutral goal and become a viable alternative to land transport [134–136]. The technologies required are still being developed, though some demonstrators are already sailing [137] .

In simple terms there are five main types of wind propulsion technology (rigid sail, soft sail, wing sail, kite, and Flettner rotor). The first three are installed on the deck and are forms of sails or wings. They require masts that are generally made from carbon fibre reinforced composites.

To fulfil the IMO objective [133], it is important to remember that IMO requires several solutions besides auxiliary wind propulsion; reduced ship speed, and reduction of the current number of ships sailing. Auxiliary wind propulsion can be a part of the solution but the savings are limited [138], and numerous factors have an impact on its performance. The trading route taken [138], ship design (required power, hydro and aerodynamic behaviour), sailing technologies, and crew willingness to reduce consumption are all determining factors for this sector. The required CO_2eq trajectory seems impossible to respect if the number of civilian ships navigating across the seas is increasing by 40-50% by 2050 [139].

Wings and sails are distinguished by their materials and stiffness. A flexible textile is easier to handle but can age rapidly due to UV exposure and mechanical loading. Some wings are made more solid by air expansion to stiffen them. Rigid wings are more robust and can be oriented to capture the wind efficiently. Kites have the advantage of not taking space on the deck and can find more stable and stronger wind at altitude.

There is a current trend towards adopting technology developed for the manufacture of very tall yacht masts in the maritime transport industry to support sails or wings. Carbon fibre composites are the preferred material. For this application the notion of sustainability is related to reducing the energy consumption of the ship by switching to wind propulsion. Such a rigging system is complex as it must be possible to reduce the sail area to adapt to navigation conditions, or to lower the mast to pass under bridges. To be acceptable to the ship owner the increased rigging cost should be covered in 5 years at most. Once the technology is mature and reliable the real gains in terms of impact reductions should be evaluated for the whole life cycle, not just the reduction in fuel costs.

The Solid Sail/ AeolDrive mast (figure 16) developed by the *Chantiers de l'Altlantique* (Saint Nazaire, France) is a recent example (prototype delivered at the end of December 2022) of a knowledge transfer from racing yachts to naval construction (between two very different sectors) [140]. This mast (Figure 17) is composed of a metallic base and a carbon/epoxy tube more than 66 meters long (2 meters wide, with 20 tonnes of carbon/epoxy), for a total height of around 73 meters. The rigid sail is made of panels which can fold together. The membrane of these panels is made from glass/epoxy composite, the frame is carbon/epoxy. The sail surface area is 1500 m² (around 450 m² for the jib and 1050 m² for the main sail), usable in winds up to 35 knots (beyond this the area is reduced). Designed for cruise ships, but also available for cargo ships, the system with balestron rigging can turn 360° and incline to 70° to pass under bridges. The first ship to use this system will be a sail powered cargo ship 136m long [141] It will go into service in the North Atlantic initially. Fuel consumption savings are estimated to be between 80% and 90%.

Figure 17

4.5. Sailcloth materials. From textiles to flexible membranes in TPT (Thin Ply Technology)

Sails were traditionally textile materials, first natural fibres such as cotton or hemp, then polymer fibres such as polyester and high-performance fibres, but today racing yachts use composite membranes based on Thin Ply Technology (TPT).

4.5.1. Specific properties of sails

A sail should keep the aerodynamic profile it was designed for. Locally each fibre will be stretched in the plane of the sail and it is at this stage that stiffness is required. The performance of mainsails and tacking sails are sensitive to this parameter, which enables the vessel to sail more closely into the wind and limits wind energy losses caused by damping and unstable sails during squalls and calm periods [27,142].

A membrane sail is a stack of materials which exploits the high rigidity of composites in the plane to obtain a three-dimensional object which is also very supple in flexure, allowing sails to be folded and stored in a small space when not used.

Sails have developed significantly over time, as experience and understanding have developed. [27,142]. They were originally woven assemblies, with natural fibres, gradually replaced by synthetic fibres such as polyester (e.g. Dacron™ see Figure 18).

Figure 18

These were not very stiff but could be coated to fix the fibre directions. Heating steps were also used to improve stiffness. The next step was the development of laminated sails, with structural fibre reinforcements. Fibres could then be placed in the loading direction and bi-radial and tri-radial cuts appeared. Stiffness could be blocked using resin. The final development was membrane sails with oriented fibres (Figure 19). High performance fibres are continuously deposed in directions which correspond to the main loading directions. Anisotropy is limited by the application of an isotropic film (Mylar™) [143] or by the addition of off-axis fibres to limit twisting and improve robustness. These three types of sail can all be found today, the choice depending on the end use and budget. Numerical modelling is used in high performance sail design to optimise orientations and fibre quantities [144,145]. However, the complexity of the materials and their loads means that design tools are not always available and simplified models [146] and the experience of architects still play an important role.

Figure 19

Sails are exposed to a range of loads in service, both mechanical (flapping, creep, bending) and environmental (seawater, UV) [147]. A combination of fibres such as aramids (Technora™) and UHMPE (Dyneema™) can be used to optimize long term properties.

4.5.2. Sails for the future

Although wind power is available as a means of propulsion and does not emit carbon during navigation, the use of sails is not neutral. A set of sails for an Imoca racing yacht represents 7 tonnes equivalent of CO_2 [127], and the loss of a sail at sea contributes to the diffusion of microplastics.

A change in the attitude of skippers and sponsors is leading to new rules [148]. These will be discussed in the section 4.7.

For each application the solution should be adapted to the requirements. For example, the choice of polymer can be a petroleum sourced thermoplastic plastic for pleasure boats sailing at European latitudes where high temperatures are rare but bio sourced thermoset polymer if more severe temperatures are expected. The former can be recycled whereas the latter has reduced impact due to bio-sourcing. Evaluation of the difference between the impacts of the two options will depend on the details of the polymer manufacture and service conditions and requires detailed LCA.

This also raises the question of end of life management of sails. Today some are re-used for bags or garden furniture but this solution is limited. In the future it may be possible to re-dimension used sails or re-coat them for re-use, with racing yacht sails being modified for pleasure boat use. End of life may be bio-assimilation through composting.

More virtuous sail management also requires class rule changes (see section 4.7), to limit the number of sails and their renewal frequency. Integration of sensors may also help to detect damage and optimise service life.

4.6. Thin Ply technology

An alternative material approach based on TPT (Thin Ply Technology) (Figure. 19) is also being developed to make some hulls (composite materials) for racing yachts.

The limitations of this technique are the high material cost, and long lay-up time, particularly for complex shapes, though it may be possible to drape plies by AFP [149]. Moreover, this technology is generally not accepted by the rules of the racing yacht classes to avoid excessive costs.

Ply thickness can have a significant effect on the structural performance of composite laminates [150,151] The development of thinner plies is based on a size effect, with matrix-dominated properties being particularly sensitive to defects (resin-rich zones, porosity, etc). Rodini and Eisemann [152] used a probabilistic method to show that laminates with thick plies are likely to contain statistically more defects than laminates with thin plies. Consequently, the thicker plies are likely to exhibit much lower failure stresses.

The Advantages of Thin Ply Technology are

- Improved mechanical properties:

– Thinner plies are acknowledged to have higher resistance to matrix cracking [153]. More generally, higher fibre dispersion and uniformity of plies results in stronger laminates due to the improved resistance to matrix cracking and delamination, and less resin rich areas [154].

– The thin-ply prepregs are also useful for improvement of compressive strength properties [153].

– It was also demonstrated that the impact resistance of CFRP laminates can be improved using thin-ply technology [155], and these authors demonstrated that damage resistance under both static and fatigue loading in tension can be improved using thin-ply prepregs.

  - Thin plies allow the production of bio-inspired Bouligand thin-ply CFRPs laminates (Bouligand microstructures of laminates) [156]. After low velocity Impact tests, this laminate shows a better damage tolerance and reduced delamination areas.
  - The residual strength (compression after impact) can increase [150].

- The laminate design can be simplified by using higher strain allowables without the need for a progressive failure analysis [157].
- The ply thickness is more regular with improved surface appearance due to the uniformity of the tow spreading.
- Potential to use heavier tow yarn, such as 100 K and 200 K, to cost-effectively obtain spread tow [154].

Most research into thin-ply laminates has focused on their benefits. The adverse effects of using thin plies has received less attention. However, studies into potential reductions in open-hole and notch sensitivity and interlaminar fracture toughness present a reduction of 10% in strength and a crack failure perpendicular to the loading direction with TPT, instead of a debonding of the fibres [158].

4.7. The role of class rules

The aim of this paragraph is to show the influence of classes on technological developments and materials selection.

In offshore racing, class rules play a defining role in determining the safety, the performance and the equity of the boats and the competitors. The rules then adopt the technologies and materials that can be used, permitting rules that withstand safety, time, and competition. As such, the America's Cup boats between 1951 and 1958 were built in wood, then during the 1970's in aluminium alloy to save weight. In 1987 (26th edition, held for the first time outside the United States in Australia), New Zealand boats were reinforced with R-glass fibres. As recently as 1988 carbon and aramid fibres were still prohibited. Since then, the racing boat classes have developed a strong understanding of composite structures, notably the use of carbon fibre within the industry.

This paragraph looks more specifically at the role of offshore racing boat classes, through the use of class rules and materials. The International Monohull Open Class Association [159] is the basis for this discussion, with links to the Class40 and the Ocean Fifty, for their differentiation in approach and in design.

Traditionally, offshore racing classes have been embedded in the world of sailing which is: *"*directly involved in science and technology. For over a century now, the race for speed records on the water and the fastest trans-oceanic crossing times have always been a major challenge*"* [160]. It is that class rules have been a driving force behind class development and the performance angle taken by sailing.

Today, classes are being challenged by a slightly more abstract criterion based on sustainability: "meeting the needs of the present without compromising the ability of future generations to meet their own needs*"* [6]. Sustainable criteria are arising, since the emergence of environmental issues such as global warming are becoming prevalent societal values [161]. In some cases, questioning what some economists and socio-economists claim: *"*that the sports industry depends solely on technological progress and performance sciences alone (... always faster, higher, further*)*" ([162] as cited in [160]). This new criterion is therefore propelling new trajectories within classes and reforming the more systemic values.

For the IMOCA Class, their trajectory is voted by the class members, of skipper majority, democratically and amended over a four-year period following each annual general meeting. In recent years, the adoption of new class rules imposing mandatory Life Cycle Assessments (LCA) for new constructions (International Monohull Open Class Association Class Rules 2025, 2021), has been accepted, to allow for a greater understanding about the impacts that are associated with the builds. The focal goal at the end of the studies is to apply ample constraints to the largest environmental hot spots within construction. This is leading the class to consider limiting the choice of carbon fibre used within structural construction, and opting for alternative methods of mould and plug construction. Such criteria may eliminate the entire production of a mould or plug or favour material alternatives, like recycled carbon or natural fibres. IMOCA have equally pulled together elements to favour impact reduction in sail manufacturing. Their Green Sail rule encompasses peripheral elements such as energy, transport and waste, by touching just three areas with 30% of emissions for each kilo of sail produced [163].

The continual fostering of innovation and contribution to maritime heritage are two key elements and the essence of the IMOCA rule creation, as this incites the teams to push the development boundaries. One example is the IMOCA Class accepting the use of alternative materials for removable parts. Teams like *11th Hour Racing* integrated these alternative and lower impacting materials into their workstream [127] to create parts like hatches with flax and biobased epoxy resin.

Yet, other classes have opted for other approaches that may be seen to be stricter or more radical, which do not prosper innovation but directly hinder any unnecessary environmental impacts. The Ocean Fifty class has banned a sail within their official sail set [164] and further to this, the Mini 6.50 Class accepts only the headsails produced in polyester and nylon [165].

For others like the Class40, carbon fibre is not permitted in the hull construction, the fibreglass hulls have a lower environmental emission potential and their performance is of relative interest during transatlantic races. Despite this, the adaptability of fibreglass for other class hulls, IMOCA for example, remains debatable, due to the nature of the design and the relative charges associated with circumnavigating the globe.

For a class, not only IMOCA in this case, but a challenge which often arises is to not restrict but to contain drift and respond to social issues, remaining in step with society. Through the democratic structure within the class these factors are naturally integrated into debate. In turn creating momentum and facilitating change, a type of team coordination that can be succinctly related to that of crewed racing which remark in their observations of collective action in offshore racing [166]. The ability of sailing teams to make coherent decisions to the given problem by effectively using the present grey matter and technology. By stretching the rules to the most elaborate means, developments can be furthered in a way that is not typically seen. This is placing offshore racing in a privileged position whereby it can enable technological developments for the global sailing industry.

4.8. Environmental impacts of production of reinforcements, matrix polymers and manufacturing.

Fibre manufacture, particularly carbon, has a significant environmental impact as mentioned in paragraph 4.2.4. This is illustrated below without detailing all the fibre grades available. Today most carbon fibres are produced by carbonization of a PAN (polacrylonitrile) precursor. In order to evaluate their CO_2 equivalent all the steps in production of 1 kg of fibres must be quantified (Figure 19). The result obtained by Ghosh et al. [120] was around 460 MJ/Kg while Rani et al found 400 MJ/Kg [167]. Figure 19 shows that 300 MJ/kg are required to produce the precursor and the remainder, 160 MJ/kg, for the high temperature conversion. Additional values can be found in [120,121,168]. These figures (Figure 20) are impressive but need to be confirmed by LCA of the industrial process and a study of fibre properties.

Figure 20

Alternative processing technology to reduce energy consumption is also possible. Ongoing research is investigating alternative carbon fibre production routes to reduce the environmental impact. Three aspects are receiving particular attention:

- The choice of precursor. For example, the use of biobased precursors made from lignin can reduce CO_2 emissions [169].
- Development of alternative heating techniques such as microwave heating to convert the precursor to carbon fibre [170,171]. Microwave heating is one of such way to decrease energy consumption and other associated challenges encountered during stabilization. Using this technology and pilot tests, Mitsui Chemicals announced a 50% reduction in energy consumption and 90% lower CO_2 emissions for the conversion step [172]. The properties of the fibres produced were not detailed.
- Another approach is to use recycled carbon fibres, this will be discussed in more detail below.

The adoption of alternative matrix polymers also provides considerable scope for reducing environmental impact. The possibilities of recyclable thermosets and thermoplastics have been discussed in section 3.3 above, but the development of recyclable epoxies is of particular interest. La Rosa et al [43] performed several studies on these materials and clearly showed their potential. For example, the recovery and re-use of the carbon fibre reinforcement with a mild acid solvent (vinegar) at low temperature (70-100°C) allowed large reductions in equivalent CO_2 in manufacture of a new composite panel due to reduced energy consumption [173].

As described in section 4.2.4 the transformation of composites produces significant environmental impacts and various studies have examined different technologies [20,126,174–178]. It is difficult to compare the results from impact analyses with different functional units and databases but in general the manufacturing process will have less impact than the production of carbon fibres. In order to quantify impacts a global approach is needed, which includes the manufacture of semi-products such as prepreg, cutting, preforming, cure, machining, the moulds and the consumables used.

4.9. End-of-life management of carbon fibre reinforced composites

It is essential to integrate recyclability at the design stage. The high cost of carbon fibres, the energy needed to produce them and the environmental impacts of their production justify their recovery at the end of life. The market for recovered fibres can therefore absorb the composite treatment costs and still remain commercially viable. This is the case for all the sectors using carbon fibres. When discussing waste fibres it is important to distinguish:

- The bobbin ends, with dry fibres, which do not require further treatment.
- Non-cured prepreg, which have reached their maximum storage limit
- Machining waste, with very short fibres.
- Composite components with long fibres which require treatment to separate the constituents. In the following we will focus on this type of waste with thermoset matrix resins.

Figure 21 shows recycling routes for such composites [179,180].

Figure 21

Mechanical recycling (grinding) which does not allow separation of the constituents is of limited interest. Thermal recycling or pyrolysis involves decomposition of the matrix in an inert atmosphere, at between

400 and 800°C according to the type of resin. Chemical recycling consists of a chemical decomposition by a reactive solvent, generally at high temperature and pressure. All these recycling methods require energy, have an impact on the environment, and result in loss of mass and degradation of the material properties. They have limitations such as:

- The chemical and thermal treatments can provide long fibres but they are not continuous. There is therefore a reduction in aspect ratio during each recycling operation.
- The fibre coating (sizing) is removed and the fibre surface after recycling may not be uniform (residual resin) [181]. The sizing is essential for textile operations and to optimize wetting and impregnation.
- The mechanical properties of the fibres are more or less affected by the recycling operation; Zhang et al [180] and Rani et al [167], have compared residual carbon fibre tensile properties after different processes and found strength losses between 1 and 85%.
- All fibre recycling operations impact the environment [182,183].
- The different recycling methods require varying amounts of energy, between 0.07 and 3.03 MJ/kg of composite for mechanical, 3 to 30 MJ/Kg for thermal and 63 to 91 MJ/Kg for chemical [167]. These values can be compared to the 400 MJ/Kg required for virgin carbon fibres. Kawarjiri et al [184] provided LCAs for pyrolysis and solvolysis.
- Recovered short fibres can be reused in mat reinforcement or for injection [185] but do not provide the full reinforcement potential of continuous carbon fibres.

The manufacture of a preform from recycled fibres is complicated as the fibres do not have the benefits of alignment on bobbins. It may therefore be necessary to realign them using additional carding operations [180,186]

- There remain several difficulties in developing an industrially viable solution to provide recycled fibres. It is not easy to know exactly the grade of fibres supplied, which is a problem for high performance applications, and limiting transport between waste production and recycling plants is not always possible. Nevertheless, the high demand and rising energy costs will favour increased production in the future.

In a recent experimental study recycled carbon fibres (dry factory waste) were used to reinforce a 6.5 meter racing yacht in 2018 [187].

5. Long term behaviour under severe loading conditions

The concept of sustainability requires a composite component to maintain a given level of performance for a given period, and it is on this basis that an LCA can evaluate the environmental impact and compare alternative material solutions. However, the evaluation of long-term behaviour of composites in a marine environment is not always straightforward due to uncertainties in loading conditions. Durability is therefore a key aspect in reducing impact, as un-planned maintenance or replacement can invalidate the LCA assumptions. This is particularly important for highly-loaded structures such as tidal turbine blades and deep-sea equipment [188], Figure 22.

Figure 22

The former are the subject of considerable research, as various tidal energy prototypes are being evaluated at sea [189].

The prediction of long term durability has been studied for many years, and is based on optimization of laboratory aging conditions to accelerate the aging mechanisms while trying to avoid the introduction of damage by excessive severity. Raising water temperature is the most common approach, while pressure, water composition and specimen geometry can also be used to accelerate water ingress. This is a vast subject and not the main aim of this review. The reader is referred to publications which discuss the accelerating factors in more detail [190–192].

Immersion for ten years or more while subjected to both tidal movements and turbulence provides a complex coupled loading configuration. Data on coupling between wet immersion and mechanical loads are rare, so safety factors tend to be high and more materials are used than necessary. Various recent studies have shown that coupled conditions can lead to premature damage and failure so this is a critical area for research if design of composite marine structures is to be optimized [193].

The potential market for tidal turbines is large in many countries and in the context of the energy transition, it is important to minimize their environmental impact. This is an important subject of ongoing research.

6. Ways to reduce the impact on the marine environment.

6.1. Natural fibres and biocomposites

Given that the majority of composite structures are based on polymer matrix and inorganic fibres today it is important to address the pollution of the oceans. The presence of microplastics is frequently invoked in the press and is an active research topic. It will not be treated here but more details can be found in [194–196], Microplastics are usually defined as small particles, of dimensions less than 5mm, formed by fragmentation. The main risks associated with these particles are:

- Ingestion by living creatures
- The impacts of toxic additives
- Adsorption and desorption of pollutants
- Transport of invasive species.

One solution could be the substitution of existing materials by biopolymers and biocomposites, provided that the biodegradability of such materials is established and understood. This requires knowledge of the biodegradation steps in a marine environment, namely their fragmentation (abiotic and/or biotic, with the participation of living organisms), their degradation (abiotic and/or biotic) and their bio-assimilation (biotic). The importance of the eco-system in these processes must be underlined, eco-systems which vary with their geographical zone, the seasons, the temperature, currents and immersion depth.

The use of plant fibres as reinforcements seems logical, as these natural materials have the capacity to biodegrade over time in nature, (though the times can be quite long). Wood has been used for centuries in marine structures but for composites the first step was to evaluate their reinforcement capability. This is not recent work, as the first polymers (developed in the early 1900's) had low strength and stiffness. They were reinforced by plant cell walls (paper, cotton fibres), and were used in marine applications such as gears, watertight seals and winch drums [23]. During the period from 1936-1941 flax fibres were used to reinforce primary aircraft structures [23]. Today various boats are reinforced by natural fibres (mainly flax) [197,198]] and figure 23 shows the racing catamaran *We-Explore* (length 18m) built in 2020 with a flax/epoxy deck (the hull is made from glass/epoxy and the sails are also partly reinforced by flax. This boat arrived second in its category of the *Route du Rhum 2022* (transatlantic race from Saint Malo (France) to Guadeloupe). It is a prototype to show the potential of natural fibre reinforcements to produce large marine structures, with low weight, and applicable even to the severe conditions of yacht racing.

Figure 23

Although various natural fibres are used in the textile industry those with the best mechanical properties and a high aspect ratio (length/diameter) are preferred (flax, hemp, nettle and ramie for example) [199,200]. These fibres show a particular mechanical behaviour which must be considered during design [201]. More information on the variability of their properties, a theme often questioned when natural fibres are discussed, is available in [202].

If the matrix is thermoplastic then the biocomposite can be considered to be recyclable; it can be recovered several times by mechanical grinding and reused by thermomechanical processes (injection, extrusion) [203–205]]. After each grinding step the fibre length decreases, but as natural fibres are present in bundles these tend to separate and the aspect ratio and mechanical properties can remain reasonably constant for several cycles.

Biocompostable polymers, which biodegrade under industrial compost conditions, can also be used as the matrix [206]]. Even though both fibres and matrix may be compostable the biodegradation kinetics of the two phases (and the composite) may not be the same and the composite may not satisfy the requirements of composting standards which define the environment, the time and the resulting eco-toxicity (e.g.

[207,208] for example). Predicting the lifetime of biodegradable composites to be used in a severe environment is not trivial. The aim is to have a long service life but then to trigger a rapid degradation mechanism as soon as the useful life ends. This paradox has been studied by Pantaloni et al [209] for different biocomposites (matrix PHA, PBS or PLA compared to PP) for different compost conditions.

In parallel with the growing interest in natural plant fibres there has been increased attention given to basalt and volcanic rock-based fibres recently in the marine industry, as an alternative reinforcement [210]. These are not strictly natural fibres as they are not present in the earth's crust. Their manufacture is similar to that of glass fibres [211,212], melting occurs in the range 1450 – 1500°C (higher than the 1250 to 1300°C needed for glass fibres).

The mechanical properties of basalt fibres are quite similar to those of glass, indeed both are largely formed of SiO_2, and durability studies have indicated similar aging performance for the two fibres [213,214]. However, according to some authors basalt fibre production is less impacting than glass fibres for the environment. One of the arguments in favour of this is that less energy is required to manufacture the basalt fibres [210]. However, this will depend on furnace technology and local energy availability. Another benefit cited is that no secondary materials are added during production [215]. Partial results from a comparison study with glass fibres [216] indicate some toxicity benefits, but more studies are needed to confirm this advantage for basalt fibres over glass. While basalt is currently being marketed as an environmentally attractive reinforcement, the benefits appear limited, and will not significantly improve the carbon footprint of marine composites.

6.2. Biodegradation in a marine environment

6.2.1. General information

From an environmental viewpoint a good material candidate for marine structures will be a bio-sourced polymer, which is completely recyclable at the end of its service life and can be used to manufacture new structures. However, due to the severe nature of the marine environment structures are frequently lost at sea, which imposes a third criterion: the material should also be completely degradable if the structure, or part of it, are lost at sea.

Biodegradation involves a series of processes which de-structure the material resulting in its complete assimilation by living organisms (Figure 24). The elements which make up the material return to their natural cycles (e.g. the carbon in wood). For polymers (and polymer composites) there are three main steps, as noted in the previous section: fragmentation (the de-cohesion of the material at the macromolecular scale), deterioration (carbon chain breakage) and assimilation (mineralisation by micro-organisms of the oligomers produced by the preceding degradation steps). More details can be found in [217,218]. The important points are:

(i) These mechanisms depend on external factors which can be separated into two categories; biotic (which implies the action of living organisms), in particular for the deterioration and assimilation, which depend on the micro-organisms present, and abiotic factors, in particular for fragmentation (external mechanical stresses, photo degradation, …) and under certain specific conditions (temperature and pH for hydrolysis and chemical oxidation).

(ii) The mechanisms are interdependent: assimilation cannot occur without the creation of sufficiently small oligomers during deterioration and fragmentation steps.

(iii) Biodegradation depends on assimilation and hence on the presence in the degradation environment of appropriate micro-organism communities [218–220].

Figure 24

The “marine environment” covers a wide range of conditions [3]. There is an important distinction between the surface zones, where UV light encourages plankton and associated communities, and significant temperature variations exist, and deep water (below 200m) where the micro-organisms are different and fewer but the environmental conditions are more stable and less favourable for degradation (lower temperature, less nutrients, risk of anaerobic conditions). Globally marine conditions are more severe than land-based.

In contrast to other conditions, such as industrial compost for example, [221], there is no widely-accepted method to certify biodegradation in a marine environment. Various international standards allow biodegradation to be characterized in the laboratory for different marine conditions such as [222]] and [223]] or [224], together with one method in-situ [225]. However, recent work and review papers have called for new tests [218,220,226,227] and shown the limitations of these methods based on the following arguments:

(i) They are not sufficiently well-defined with respect to the micro-organisms used for tests [218], [227].

(ii) The test conditions are not representative of real conditions (nutrient concentration, temperature, oxygen level) [226,228,229].

(iii) They do not include the fragmentation and deterioration steps, but focus only on assimilation.

Some recent studies have tried to improve the standard methods by combining laboratory and in-situ conditions [228], [229] or by natural selection of the micro-organisms [230].

6.2.2. An example: biodegradation of wood

An example which illustrates the study of marine biodegradation is that of wood. This material has been studied for many years as it is used for different marine applications including ships and port infrastructure. Shipwrecks have been discovered apparently intact after hundreds of years buried in sediments. Studies of these, combining materials science and archaeology, have shown that only the lignin in the wood is intact, the cellulose having been completely consumed by micro-organisms. For more common cases, when the wooden structure settles on the seafloor, the degradation process is faster: several series of organisms degrade the structure, first macroscopic (bivalve, marine worms) then microscopic (fungi, bacteria). Large structures disappear in a few years [231,232]. This example clearly shows the importance of the environment [233].

6.2.3. Degradation of biopolymers in marine environment

Studies on the biodegradation of biopolymers in a marine medium are relatively recent. Given the wide range of environments and the lack of representative laboratory testing protocols the results are quite variable [227,234].

Some promising materials can be cited, such as the PHAs, and PCL [230,235]. Others, such as regenerated cellulose PBS or PBAT, show signs of biodegradation in certain environments such as coastal regions, ports, or close to human activities [236]. Plastics such as PLA or the range of conventional plastics show few signs of degradation under in-situ conditions and cannot be considered as biodegradable at sea.

In summary, the essential outstanding questions are how to evaluate in the laboratory the biodegradability of a polymer composite lost at sea, how can we accelerate such tests and how can the different physical, chemical and biological mechanisms be separated in order to develop predictive lifetime models. This is a major ongoing research topic.

6.3. An optimal cycle for biosourced materials recyclable and biodegradable

Figure 25 shows a theoretical scheme for a circular biocomposite economy (sourced from renewable resources) reinforced by natural cell walls and impregnated with a biobased, thermoplastic, biocompostable matrix.

Figure 25

While this model appears very attractive there are some limitations. The aim is to escape from the current strong dependence on oil and the “extract-transform-use-discard” model. The scheme is inspired by the plant development cycle. This is an open cycle, as in order for the plant to grow it needs a minimum (and maximum) temperature, sunshine (for photosynthesis), rain (or water from the soil), minerals (nitrates, phosphorous…). Even though recycling is possible (a non-neutral process for the environment), at each step there is always some loss of material, loss of performance and a need for energy. The circular economy scheme neglects these factors as well as limits on physical properties and technological capacity. In the case of composites, the waste products are complex as they include more than one material phase. Even if the two phases are biocompostable, their biodegradation kinetics will not be identical, as they will depend on the composting conditions.

Current knowledge on the use of biocomposites (100% biobased, recyclable, biodegradable) for marine structures with a lifetime of 30 years or more is very limited. Nevertheless, it should be noted that ships have been built from wood (100% biobased and biodegradable) for centuries, even though it is necessary to treat the wood, by painting for example, to slow the degradation or to help in assembly by bonding. Many internal boat fittings are made from plywood certified for marine use. The adhesive used does not allow biodegradation and incineration is generally the end of life envisaged in LCA [237]. This is also the case for moulded wooden hulls, their assembly frequently uses epoxy adhesives. In general wood is considered to be the most important renewable resource for a durable economy in the future [238]. It is traditionally used in the construction industry where its use has gained importance in recent years as a durable alternative to steel and concrete. It also serves as the basis for new functional biological materials. For example, tree trunks are multi-functional, combining mechanical support, sap transport and storage (of starch for example). The abilities of plants such as self-healing and adaptation either to their orientation with respect to gravity (gravitropism), or to external stimulation (thigmomorphogenesis) are also inspiring for future composite structures [239,240]. However, the sustainability of wood as a green resource is often reduced by the treatments mentioned above and non-durable modifications. Reflections are therefore underway in various industrial sectors in order to improve the possibilities for recycling and end-of-life options for wood products. Marine construction could benefit from these developments and the establishment of dedicated facilities. It is already possible to imagine the use of 100% biodegradable internal boat fittings, less exposed than hull and deck structures, but at the end of life the different composite families will need to be separated.

7. Discussion

7.1. First observations

For many marine applications, high performance composite materials are the preferred solution, even if the long term behaviour data and predictive tools remain limited. However, in all sectors there is an urgent need to introduce eco-design methods, based on LCA to quantify potential environmental impacts.

Superficial arguments to justify material choices ("green-washing") are no longer acceptable. The aim must be to first reduce the flow of raw materials and energy over the lifetime of the structure. It is not easy to demonstrate sustainability, particularly for structures that will be in service for 20 years or more. And comparing a new solution with an existing one requires a robust set of data (on material manufacture, performance over time, service loading conditions and end of life options…). For the latter, new technologies, recycling of carbon/epoxy for example, may not be available at an industrial scale, and their viability will depend on the regular availability of a minimum amount of material. They require an appropriate economic model and solutions for all the recycled products and by-products. This is not specific to the marine industry but the need to adapt to the wide range of materials in boat hulls, to cater for seawater aged materials, and the long lifetimes of many boats provide additional constraints.

7.2. Availability of new polymers

Low cost plastic materials with reliable properties are employed in many everyday products. Multi-billion-dollar companies are established around these plastic materials, and each polymer takes years to optimize, secure intellectual property, comply with the regulatory bodies such as REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) and the Environmental Protection Agency, and develop consumer confidence. Therefore, developing a fully sustainable new plastic material with even a slightly different chemical structure is a long and costly process. Hence, the production of the common plastic materials with exactly the same chemical structures but from alternative feedstock, which does not require any new registration processes better reflects the reality of how to address the critical future of sustainable plastics. Hayes et al. [241], recently highlighted the example of the synthesis of common monomers using chemicals from sustainable feedstocks that can be used as a like-for-like substitute to produce conventional petrochemical-free thermoplastics.

7.3. Sustainability as part of the hull design process

Naval architecture projects can be considered as a series of approximations which can be presented as a design spiral, Figure 26, [242–244].

Figure 26

Sustainability of a composite vessel is defined to a large extent by the activity shown in red, the definition of materials, manufacturing and scantlings. This is a creative process and includes decisions on maintenance, and end-of-life. The design of mechanical structures is well documented [245,246]. It can be described by flow diagrams with feedback loops. Figure 27 shows the steps towards sustainability in more detail. This summarizes the way in which the potential solutions described above can be integrated in the design process.

Figure 27

The designer must satisfy a need, defined by the end user together with other interested parties such as regulatory bodies, marketing, sales etc. Performance criteria are specified and these must include sustainability from the start of the design process. Other criteria will include static and dynamic loads, lifetime and service conditions. Based on the different options described in the previous sections, the main considerations at this specification stage are the reduction of waste, at each step of the process, an analysis of the life cycle, an extended service life and the inclusion of end-of-life options in the initial design. The design process will then consider available options and select materials, manufacturing processes and tooling, but also maintenance, repair possibilities, re-use and disposal. A specific evaluation of the environmental impacts of the composite structure throughout its lifetime will be performed. This will include carbon footprint, [247] and LCA, [14,248]. There are also links between these standards, the ISO 14067 [247]standard for example.

There are different approaches to LCA according to the application [129]. The Product Environmental Footprint method is favoured in Europe.

Performing an LCA is not always easy, the lack of reliable data, the development of new materials and processes and the difficulty in projecting towards the future for structures which may navigate for 60 years or more requires assumptions which may not be realistic. There has been some discussion of prospective LCA's in the literature, for example for biobased carbon fibres [249], lightweight structures [250] and methodologies [251].

To include the economic component in the evaluation of alternative options, Life-Cycle Cost Assessment (LCCA) needs to be performed along with LCA. The combination of the results obtained from these two assessments offers sustainable decision-making support for alternative technology implementation, e.g. alternative fuel in a ship power system [252,253]. The LCCA investigates the total costs (sum of investment, maintenance, operation costs, end of life) during the lifetime of a ship.

Another important step, in the design process is Safety-by-Design. This involves identification of risks and uncertainties early in the design process in order to reduce potential dangers [254,255].

These are the main steps which allow the designer to include sustainability in the design of a composite hull structure. The following steps in Figure 27 cover analysis and the decisions to be made based on these (often incomplete) data sets.

7.4. Refit and repair of composite boat hulls

In terms of sustainability one attractive option is to extend the lifetime. This can be applied to composite boats and one of the advantages of composite materials is the possibility for repair.

At the end of their service life several scenarios are available:

- Taking composites to landfill sites is one end-of-life solution today (see section 3.2). This may reduce greenhouse gas effects in the short term but results in a chronic waste of valuable material resources. Also, the organic materials involved are not inert over time and may present a risk for both humans and biodiversity.

- Recycling of composites, discussed in section 3.3 is complex. It is an attractive approach to limit the use of virgin resources, but recycling efficiency may be low and the losses (of materials and performance) during each cycle, the need for energy and the environmental impacts should be considered. The associated costs and the need for a regular supply of materials to an industrial recycler should also be taken into account.
- Incineration (see section 3.2), is another scenario which can recover energy, but may generate greenhouse gases.

An alternative scenario is refit and repair. This involves investment in work to return the structure to its initial state and hence extend its service life. It can reduce the environmental impact compared to the construction of a new vessel. The following section will briefly describe this scenario.

A first point to consider is the reasons for withdrawing a vessel from the active fleet. This has been discussed by Martínez-Vázquez et al [256]. The reasons vary according to the type of ship and three categories were examined:

Professional vessels (fishing, military, transport, lifeboats, …) have generally long service lives (unless subjected to major accident damage). The arguments may be fiscal, the vessel cost has been written off, the need for extensive renovation (new propulsion or other equipment for example, or uncertainties over the mechanical state of the structure). For fishing boats there may also be a political will to reduce the size of the fleet with strong financial incentives.

Racing vessels (Figure 28.a), yachts for example, can be monotypes (series) or prototypes. The latter tend to be declassified more quickly as they rapidly become less competitive than more recent boats; classification rules can also change, and there is little demand for prototypes as they cannot be used easily as pleasure boats (difficult to navigate, requiring expert sailors). This sector is also very sensitive to design improvements and new technologies.

Pleasure boats (Figure 28.b) can be declassified for both technical and non-technical reasons. The latter include financial reasons, inheritance difficulties, lack of port space, low annual usage… Technical reasons include damage to the structure, uncertainty over performance after repair or the difficulty to find a boatyard to do the repairs.

The state of a vessel after several years in service will depend on its design, construction quality, service conditions and the maintenance it has received. As a result, removal from service is not the only option when a boat has been damaged; in some cases repair may be possible.

Composites are a relatively new type of material (since the 1960's) and are constantly evolving. The fibre reinforcements and matrix resins used 40 years ago differ significantly from those used today, even if the generic names are similar. A loss in properties may involve accumulated composite damage (matrix cracks, fibre debonding…) and the aging of the constituents, matrix hydrolysis for example). Repair is concerned with restoration of the behaviour of the structure, not replacement of the materials. Analysis of a refit requires a preliminary estimation of the mechanical performance of the structure in order to define the necessary repairs and estimate the lifetime extension which they will allow.

There are other possible uses for end-of-life pleasure boats; the *Batho* boatyard in Nantes (France) [257] transforms yachts and motor boats, mainly dating from 1970 to 1980, into tiny houses. The idea is that each boat already has a roof, walls and floors which only require renovation. This approach is equivalent to a long storage, which delays the final deconstruction but it only involves a small number of vessels each year.

Figure 28

7.5. End of life management

The recycling options discussed above are shown in figures 8 and 24 and they represent the current state-of-the-art for closed loop composite waste management. The main challenges are due to the heterogeneity of waste, the small quantities available, the diversity of sources and contamination (degradation, aging of polymers, water content …).

Recycling corresponds to several of the 17 durable development objectives defined by the United Nations. The numbers correspond to [21]:

- Goal 7: Affordable and clean energy: Ensure access to affordable, reliable, sustainable and modern energy
- Goal 8: Decent work and economic growth: Promote inclusive and sustainable economic growth, employment and decent work for all
- Goal 9: Industries, Innovation and infrastructures: Build resilient infrastructure, promote sustainable industrialization and foster innovation
- Goal 11: Sustainable cities and communities: Make cities inclusive, safe, resilient and sustainable
- Goal 12: Responsible consumption and production: Ensure sustainable consumption and production patterns
- Goal 13: Climate action: Take urgent action to combat climate change and its impacts
- Goal 14: Life below water: Conserve and sustainably use the oceans, seas and marine resources
- Goal 15: Life and land: Sustainably manage forests, combat desertification, halt and reverse land degradation, halt biodiversity loss.

7.6. Functional economies

An alternative approach to reducing the impact of marine activities is being developed for the use of recreational boats based on the idea of a functional economy in the USA and Europe, and through Boat Clubs, [258]. The traditional concept of buying a product, in this case a boat, is being replaced by buying the use of a boat. This separates the added value related to navigation from the energy consumption and raw materials used to manufacture the boat. The aim is to develop integrated solutions for products and services within a sustainable framework. Thus, the economic exchange is no longer linked to the ownership, which remains with the manufacturer (or a service manager) throughout the boat's lifetime, but rather on the possibility for end-users to pay to use the product. Thus, a boat user will buy navigation time on an annual basis. The use of pleasure boats is limited by the amount of leisure time available to their owners and the result today is that these boats navigate very rarely. In a Boat Club the boats navigate frequently with different users. Their sustainability is improved as for a given number of sailors the number of boats required is significantly reduced (economies of materials but also less production waste, less energy required) and hence there are also less boats to dispose of at the end of life. As navigation time is increased the structure will require more maintenance but the scantlings (choice of materials, design) can be optimised for a better performance over a long time. For motor boats this can also result in lower fuel requirements.

7.7. Bio-inspiration

The response of a structure depends on the shape, the material composition and its structural arrangement. For a given composition the latter can be modified at different scales to adapt to different applications [259]. In nature shapes are not expensive to produce but the materials are.

Natural materials can be shown to develop a hierarchical structure during growth [260] while man-made materials can develop multi-scale structures through material engineering. There is a clear link between the living world and materials developed by human technology, in both cases the functional response is obtained by transformations. Biomimetism is defined as the transfer of knowledge derived from analysis of biological systems to human applications. However, biomimetism does not necessarily result in sustainable solutions. Bioinspired innovation may require non-renewable resources or generate toxic products. A durable bio-inspired innovation must include eco-responsible design, including production and end of life.

This is defined in a standard [261]. The analysis of natural marine structures is a rich source of inspiration in the development of new products (bio-inspiration) [262,263].

7.8. Sustainable marine structures

Figure 29 shows an overview of the different areas for which the sustainability should be examined. These are not independent, and they should be studied throughout the lifetime of the structure. This review is focussed on composite materials so the emphasis is on the material aspects, which can be short term (factory production waste for example) or long term (response of a boat hull in a severe environment whose characteristics are not completely known). A long lifetime implies that knowledge, legislation, materials, technologies and societal constraints can change. The concept of sustainability is based on a philosophy, an approach and permanent questions on: the reduction of environmental impacts, reduction of waste, increased performance and lifetime, acceptable solutions for end of life and the development of a framework, which allows continuous progress to be made in knowledge of materials, technologies, available design tools and legislation. Different actors are involved during the life of marine structures but they can no longer consider that their responsibility is limited to their individual activity sector. For example, the principle of Extended Producer Responsibility exists in French law since 1975 (article L. 541-10 of the Environment Code). This states that producers, importers and distributors can be held responsible for waste elimination of their products or the materials used in their manufacture.

Most projects start by the definition of design requirements. The complete life cycle must be included at this stage in order to reduce impacts. This is the basis of Eco-design, [14]. One area of uncertainty for marine structures is detailed knowledge of service conditions. These involve coupling at various levels (water diffusion/mechanical loading, fluid/structure) and require reliability based design.

The choices of composite constituents, manufacturing route and end of life scenarios are important steps. These are usually guided by design rules from certification societies and any uncertainties lead to higher safety factors. For a new design this step will often require supplementary testing, both to simulate the service environment and to provide the data needed for the LCA. Development of end-of-life solutions is an essential part of the design process. The composite properties are created by the manufacturing process and may not correspond exactly to those used for the design calculations so this must be checked. The mould has its own impacts and lifetime to consider and these may make a significant contribution to overall impacts, particularly for one-off racing prototypes. Re-use of moulds or re-qualification of these vessels at the end of their racing life can improve their impact. For series production mould maintenance and repair operations must also be included in the analysis. The final item on Figure 29 is the end of life management. The identification of materials, separation and recycling processes may allow re-use and this is an area requiring more research effort. It is not possible to legislate to increase material re-use unless efficient treatment paths are available.

Figure 29

8. Concluding remarks

The ability to place reinforcement in the directions corresponding to local loads has led to extensive use of composites in marine structures, particularly boats. Polymer composites are still relatively new materials compared to wood or steel, but the amount of composites reaching the end of their service life is growing steadily, without the industrial facilities to exploit their potential as a resource. Innovative re-use and recycling process R&D is essential.

For new construction alternative matrix polymers now exist, in the form of recyclable thermosets and thermoplastics. More extensive use of both should reduce impacts, provided manufacturing processes are optimized.

Glass fibres are the main reinforcement used in marine composites today. Recent projects have demonstrated that natural fibres can offer an alternative with significant reductions in carbon footprint.

Racing yachts need carbon fibres to optimize performance, but their environmental impact is very high. Class rules can encourage innovative changes in materials but the “performance at all cost” approach must also be questioned as it is not sustainable.

There is an urgent need to reduce the environmental impact of the marine industry. This has been recognized, for example there is active ongoing research analyzing the complete life cycle and developing new propulsion systems. However, boat and ship structures also contribute significantly to the carbon footprint and legislative pressure is needed to accelerate the transition to lower impact alternative materials. To quantify the benefits of these alternatives LCA is the main tool today. Reliable input data for these analyses are essential if genuine progress is to be achieved and justified. Alternative approaches such as “Safe by Design’, developed in other industries, should also be considered and adapted to marine construction.

There is a wide variety of materials, processes and practices used across the marine sector. As illustrated above, a global approach is essential in order to optimize performance, durability and sustainability. The urgency of energy transition and climate change, will accelerate the priority given to the search for innovative sustainable composite material solutions. Many challenges remain along the road to more sustainable marine structures, but there is encouragement from the increasing public and industrial awareness of the need to change.

References

[1] Douenne T, Fabre A. French attitudes on climate change, carbon taxation and other climate policies. Ecological Economics 2020;169:106496. https://doi.org/10.1016/j.ecolecon.2019.106496.

[2] UNCTAD (United Nations Conference on Trade and Development). Review of Maritime Transport 2023. https://unctad.org/publication/review-maritime-transport-2023

[3] Ramsses EU Project. https://www.ramsses-project.eu/ (accessed April 3, 2024).

[4] FibreShip EU project. http://www.fibreship.eu/ (accessed April 3, 2024).

[5] Bureau Véritas, NR546 Hull in composite, plywood and high density polyethylene materials Marine & Offshore. https://marine-offshore.bureauveritas.com/nr546-hull-composite-plywood-and-high-density-polyethylene-materials (accessed April 3, 2024).

[6] Brundtland H. Report of the World Commission on Environment and Development 1987. https://digitallibrary.un.org/record/139811 (accessed November 29, 2023).

[7] Laurent E. Sortir de la croisssance, mode d’emploi [in French]. Les Liens qui Libèrent; 2019. https://doi.org/10.4000/lectures.49658.

[8] Rockström J, Steffen W, Noone K, Persson Å, Chapin FS, Lambin EF, et al. A safe operating space for humanity. Nature 2009;461:472–5. https://doi.org/10.1038/461472a.

[9] Mouritz AP, Gellert E, Burchill P, Challis K. Review of advanced composite structures for naval ships and submarines. Compos Struct 2001;53:21–42. https://doi.org/10.1016/S0263-8223(00)00175-6.

[10] Gay D, Hoa SV (Suong V), Tsai SW. Composite materials : design and applications. CRC Press; 2003.

[11] NF EN ISO 14006:2020. ISO 14006:2020 - Environmental management systems - Guidelines for incorporating ecodesign 2020.

[12] Katsiropoulos C V., Pantelakis SG. A Novel Holistic Index for the Optimization of Composite Components and Manufacturing Processes with Regard to Quality, Life Cycle Costs and Environmental Performance. Aerospace 2020;7:157. https://doi.org/10.3390/aerospace7110157.

[13] REACH Regulation - European Commission https://environment.ec.europa.eu/topics/chemicals/reach-regulation_en (accessed December 20, 2023).

[14] NF EN ISO 14044:2006. ISO 14044:2006 - Environmental management - Life cycle assessment - Requirements and guidelines 2006.

[15] Hojnik J, Biloslavo R, Cicero L, Cagnina MR. Sustainability indicators for the yachting industry: Empirical conceptualization. J Clean Prod 2020;249:119368. https://doi.org/10.1016/J.JCLEPRO.2019.119368.

[16] Mio A, Fermeglia M, Favi C. A critical review and normalization of the life cycle assessment outcomes in the naval sector. Bibliometric analysis and characteristics of the studies. J Clean Prod 2022;371:133268. https://doi.org/10.1016/J.JCLEPRO.2022.133268.

[17] Busetto B, Bordignon A, Bortoluzzi A, Milanesi S, Paduano A, Mio A. Life Cycle Assessment in the Naval Sector: Between Certification and New Materials. Progress in Marine Science and Technology 2022;6:564–71. https://doi.org/10.3233/PMST220067.

[18] Favi C, Germani M, Campi F, Mandolini M, Manieri S, Marconi M, et al. Life Cycle Model and Metrics in Shipbuilding: How to Use them in the Preliminary Design Phases. Procedia CIRP 2018;69:523–8. https://doi.org/10.1016/J.PROCIR.2017.11.071.

[19] Burman M, Kuttenkeuler J, Stenius I, Garme K, Rosén A. Comparative Life Cycle Assessment of the hull of a high-speed craft. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment 2016;230:378–87. https://doi.org/10.1177/1475090215580050.

[20] Cucinotta F, Guglielmino E, Sfravara F. Life cycle assessment in yacht industry: A case study of comparison between hand lay-up and vacuum infusion. J Clean Prod 2017;142:3822–33. https://doi.org/10.1016/J.JCLEPRO.2016.10.080.

[21] United Nations. Goal 15: Sustainably manage forests, combat desertification, halt and reverse land degradation, halt biodiversity loss. https://www.un.org/sustainabledevelopment/fr/biodiversity/ (accessed December 4, 2023).

[22] Cotterell B. Fracture and life. Imperial College Press; 2010. https://doi.org/10.1142/P593.

[23] Baley C, Bourmaud A, Davies P. Eighty years of composites reinforced by flax fibres: A historical review. Compos Part A Appl Sci Manuf 2021;144:106333. https://doi.org/10.1016/j.compositesa.2021.106333.

[24] Smith CS. Design of marine structures in composite materials, Elsevier 1990.

[25] Marsh G. 50 years of reinforced plastic boats. Reinforced Plastics 2006;50:16–9. https://doi.org/10.1016/S0034-3617(06)71125-0.

[26] Thomas JAG. HMS Wilton — a glass-reinforced plastics minehunter. Composites 1972;3:79–82. https://doi.org/10.1016/0010-4361(72)90380-1.

[27] Graham-Jones J, Summerscales J, Marine Applications of Advanced Fibre-Reinforced Composites. Elsevier; 2016. https://doi.org/10.1016/C2013-0-16504-X.

[28] Reddy SSP, Suresh R, Hanamantraygouda MB, Shivakumar BP. Use of composite materials and hybrid composites in wind turbine blades. Mater Today Proc 2021;46:2827–30. https://doi.org/10.1016/j.matpr.2021.02.745.

[29] Skrifvars M, Johansson M, Blomqvist T, Säämänen A. Low styrene emission unsaturated polyester resins. Composites (Paris). 1992, Vol 32, 3, pp 42-45.

[30] Marsh G. Material trends for FRP boats. Reinforced Plastics 2003;47:23–34. https://doi.org/10.1016/S0034-3617(03)00931-7.

[31] Neşer G. Polymer Based Composites in Marine Use: History and Future Trends. Procedia Eng 2017;194:19–24. https://doi.org/10.1016/J.PROENG.2017.08.111.

[32] Cox. G & Marine design manual for fiberglass reinforced plastics. New York: McGraw-Hill; 1960. https://doi.org/10.5962/bhl.title.39107.

[33] Turner A, Rees A. The environmental impacts and health hazards of abandoned boats in estuaries. Reg Stud Mar Sci 2016;6:75–82. https://doi.org/10.1016/J.RSMA.2016.03.013.

[34] Summerscales J, Singh MM, Wittamore K. Disposal of composite boats and other marine composites. Marine Applications of Advanced Fibre-Reinforced Composites, Elsevier; 2016, p. 185–213. https://doi.org/10.1016/B978-1-78242-250-1.00008-9.

[35] Leon MJ. Recycling of wind turbine blades: Recent developments. Curr Opin Green Sustain Chem 2023;39:100746. https://doi.org/10.1016/J.COGSC.2022.100746.

[36] Ministère de la Transition Ecologique. La feuille de route de l'économie circulaire (FREC) [in french] 2019. https://www.ecologie.gouv.fr/feuille-route-economie-circulaire-frec (accessed April 2, 2024).

[37] Filière de déconstruction des bateaux de plaisance, APER [in french] n.d. https://www.recyclermonbateau.fr/ (accessed November 30, 2023).

[38] ADEME. Guide du recyclage et de l'écoconception des composites [in french] 2022:45. https://librairie.ademe.fr (accessed November 29, 2023).

[39] Eco profil – GreenPoxy. https://greenpoxy.org/ecoprofil/ (accessed December 18, 2023).

[40] Wu T, Zhang W, Jin X, Liang X, Sui G, Yang X. Efficient reclamation of carbon fibers from epoxy composite waste through catalytic pyrolysis in molten ZnCl $_2$. RSC Adv 2019;9:377–88. https://doi.org/10.1039/C8RA08958B.

[41] Pastine S. Can epoxy composites be made 100% recyclable? Reinforced Plastics 2012;56:26–8. https://doi.org/10.1016/S0034-3617(12)70109-1.

[42] Davies P, LeJeune S. Influence of seawater aging on carbon fibre reinforced recyclable epoxy composites, Internal IFREMER report. 2023.

[43] La Rosa AD, Banatao DR, Pastine SJ, Latteri A, Cicala G. Recycling treatment of carbon fibre/epoxy composites: Materials recovery and characterization and environmental impacts through life cycle assessment. Compos B Eng 2016;104:17–25. https://doi.org/10.1016/j.compositesb.2016.08.015.

[44] A winning collaboration behind the RecyclableBlade. https://www.siemensgamesa.com/explore/journal/2021/11/recyclable-blade (accessed December 15, 2023).

[45] Snyder AD, Phillips ZJ, Turicek JS, Diesendruck CE, Nakshatrala KB, Patrick JF. Prolonged in situ self-healing in structural composites via thermo-reversible entanglement. Nat Commun 2022;13:6511. https://doi.org/10.1038/s41467-022-33936-z.

[46] Priyadarsini M, Rekha Sahoo D, Biswal T. A new generation self-healing composite materials. Mater Today Proc 2021;47:1229–33. https://doi.org/10.1016/j.matpr.2021.06.456.

[47] Srinivas M, Yelamasetti B, Vishnu Vardhan T, Mohammed R. A critical review on self-healing composites. Mater Today Proc 2021;46:890–5. https://doi.org/10.1016/j.matpr.2020.12.1129.

[48] Paladugu SRM, Sreekanth PSR, Sahu SK, Naresh K, Karthick SA, Venkateshwaran N, et al. A Comprehensive Review of Self-Healing Polymer, Metal, and Ceramic Matrix Composites and Their Modeling Aspects for Aerospace Applications. Materials 2022;15:8521. https://doi.org/10.3390/ma15238521.

[49] Trask RS, Williams GJ, Bond IP. Bioinspired self-healing of advanced composite structures using hollow glass fibres. J R Soc Interface 2007;4:363–71. https://doi.org/10.1098/rsif.2006.0194.

[50] Schenk V, Labastie K, Destarac M, Olivier P, Guerre M. Vitrimer composites: current status and future challenges. Mater Adv 2022;3:8012–29. https://doi.org/10.1039/D2MA00654E.

[51] Kamble M, Vashisth A, Yang H, Pranompont S, Picu CR, Wang D, et al. Reversing fatigue in carbon-fiber reinforced vitrimer composites. Carbon, 2022;187:108–14. https://doi.org/10.1016/j.carbon.2021.10.078.

[52] Perrin H, Vaudemont R, Del Frari D, Verge P, Puchot L, Bodaghi M. On the cyclic delamination-healing capacity of vitrimer-based composite laminates. Compos Part A Appl Sci Manuf 2024;177:107899. https://doi.org/10.1016/j.compositesa.2023.107899.

[53] Jones AR, Blaiszik BJ, White SR, Sottos NR. Full recovery of fiber/matrix interfacial bond strength using a microencapsulated solvent-based healing system. Compos Sci Technol 2013;79:1–7. https://doi.org/10.1016/j.compscitech.2013.02.007.

[54] Hart KR, Wetzel ED, Sottos NR, White SR. Self-healing of impact damage in fiber-reinforced composites. Compos B Eng 2019;173:106808. https://doi.org/10.1016/j.compositesb.2019.05.019.

[55] Cordier P, Tournilhac F, Soulié-Ziakovic C, Leibler L. Self-healing and thermoreversible rubber from supramolecular assembly. Nature 2008;451:977–80. https://doi.org/10.1038/nature06669.

[56] Leibler L, Rubinstein M, Colby RH. Dynamics of telechelic ionomers. Can polymers diffuse large distances without relaxing stress ? Journal de Physique II 1993;3:1581–90. https://doi.org/10.1051/JP2:1993219.

[57] Manarin E, Da Via F, Rigatelli B, Turri S, Griffini G. Bio-Based Vitrimers from 2,5-Furandicarboxylic Acid as Repairable, Reusable, and Recyclable Epoxy Systems. ACS Appl Polym Mater 2023;5:828–38. https://doi.org/10.1021/acsapm.2c01774.

[58] Sharma H, Rana S, Singh P, Hayashi M, Binder WH, Rossegger E, et al. Self-healable fiber-reinforced vitrimer composites: overview and future prospects. RSC Adv 2022;12:32569–82. https://doi.org/10.1039/D2RA05103F.

[59] Otheguy ME, Gibson AG, Findon E, Cripps RM, Mendoza AO, Castro MTA. Recycling of end-of-life thermoplastic composite boats. Plastics, Rubber and Composites 2009;38:406–11. https://doi.org/10.1179/146580109X12540995045642.

[60] Gibson AG, Ijaz M, Dodds N, Sharpe A, Knudsen H. Vacuum bag moulding of large thermoplastic parts in commingled glass/PET. Plastics, Rubber and Composites 2003;32:160–6. https://doi.org/10.1179/146580103225002605.

[61] Bourçois D, Baley C, Grohens Y, Le Maguer G, Le Duigou A, Deux J-M, et al. Environment-friendly composites for marine applications: the Navecomat project : JEC Composites Magazine, 2011:35–7.

[62] Le Duigou A, Bourmaud A, Davies P, Baley C. Long term immersion in natural seawater of Flax/PLA biocomposite. Ocean Engineering 2014;90:140–8. https://doi.org/10.1016/j.oceaneng.2014.07.021.

[63] Le Duigou A, Davies P, Baley C. Seawater ageing of flax/poly(lactic acid) biocomposites. Polym Degrad Stab 2009;94:1151–62. https://doi.org/10.1016/J.POLYMDEGRADSTAB.2009.03.025.

[64] Le Duigou A, Davies P, Baley C. Interfacial bonding of Flax fibre/Poly(l-lactide) bio-composites. Compos Sci Technol 2010;70:231–9. https://doi.org/10.1016/J.COMPSCITECH.2009.10.009.

[65] Le Duigou A, Davies P, Baley C. Exploring durability of interfaces in flax fibre/epoxy micro-composites. Compos Part A Appl Sci Manuf 2013;48:121–8. https://doi.org/10.1016/J.COMPOSITESA.2013.01.010.

[66] Le Duigou A, Pillin I, Bourmaud A, Davies P, Baley C. Effect of recycling on mechanical behaviour of biocompostable flax/poly(l-lactide) composites. Compos Part A Appl Sci Manuf 2008;39:1471–8. https://doi.org/10.1016/J.COMPOSITESA.2008.05.008.

[67] Duigou A Le, Davies P, Baley C. Replacement of Glass/Unsaturated Polyester Composites by Flax/PLLA Biocomposites: Is It Justified? J Biobased Mater Bioenergy 2011;5:466–82. https://doi.org/10.1166/jbmb.2011.1178.

[68] Le Duigou A, Davies P, Baley C. Environmental impact analysis of the production of flax fibres to be used as composite material reinforcement. J Biobased Mater Bioenergy 2011;5:153–65. https://doi.org/10.1166/JBMB.2011.1116.

[69] Le Duigou A, Deux JM, Davies P, Baley C. Protection of Flax/PLLA biocomposites from seawater ageing by external layers of PLLA. Int J Polym Sci 2011;2011. https://doi.org/10.1155/2011/235805.

[70] Ijaz M, Robinson M, Gibson AG. Cooling and crystallisation behaviour during vacuum-consolidation of commingled thermoplastic composites. Compos Part A Appl Sci Manuf 2007;38:828–42. https://doi.org/10.1016/J.COMPOSITESA.2006.08.007.

[71] Wakeman MD, Cain TA, Rudd CD, Brooks R, Long AC. Compression moulding of glass and polypropylene composites for optimised macro- and micro- mechanical properties—1 commingled glass and polypropylene. Compos Sci Technol 1998;58:1879–98. https://doi.org/10.1016/S0266-3538(98)00011-6.

[72] Popineau V, Célino A, Le Gall M, Martineau L, Baley C, Le Duigou A. Vacuum-Bag-Only (VBO) Molding of Flax Fiber-reinforced Thermoplastic Composites for Naval Shipyards. Applied Composite Materials 2021;28:791–808. https://doi.org/10.1007/S10443-021-09890-2/METRICS.

[73] ARGO - Coriolis : In situ data for operational oceanography n.d. https://www.coriolis.eu.org/Observing-the-Ocean/ARGO (accessed December 1, 2023).

[74] Le Reste S, Dutreuil V, André X, Thierry V, Renaut C, Le Traon P-Y, et al. “Deep-Arvor”: A New Profiling Float to Extend the Argo Observations Down to 4000-m Depth. J Atmos Ocean Technol 2016;33:1039–55. https://doi.org/10.1175/JTECH-D-15-0214.1.

[75] Davies P, Riou L, Mazeas F, Warnier P. Thermoplastic Composite Cylinders for Underwater Applications. Journal of Thermoplastic Composite Materials 2005;18:417–43. https://doi.org/10.1177/0892705705054397.

[76] Arhant M, Briançon C, Burtin C, Davies P. Carbon/polyamide 6 thermoplastic composite cylinders for deep sea applications. Compos Struct 2019;212:535–46. https://doi.org/10.1016/J.COMPSTRUCT.2019.01.058.

[77] Capiati NJ, Porter RS. The concept of one polymer composites modelled with high density polyethylene. J Mater Sci 1975;10:1671–7. https://doi.org/10.1007/BF00554928.

[78] Alcock B, Peijs T. Technology and Development of Self-Reinforced Polymer Composites. Advances in Polymer Science, 2011, p. 1–76. https://doi.org/10.1007/12_2011_159.

[79] Le Gall M, Niu Z, Curto M, Catarino AI, Demeyer E, Jiang C, et al. Behaviour of a self-reinforced polylactic acid (SRPLA) in seawater. Polym Test 2022;111:107619. https://doi.org/10.1016/J.POLYMERTESTING.2022.107619.

[80] Roiron C, Lainé E, Grandidier J-C, Garois N, Voillequin B, Vix-Guterl C. Evaluation of the creep behavior of a SRPE (Self-Reinforced polyethylene) over the long-term. Compos Part A Appl Sci Manuf 2023;175:107792. https://doi.org/10.1016/j.compositesa.2023.107792.

[81] Noonan M, Obande W, Ray D. Simulated end-of-life reuse of composites from marine applications using thermal reshaping of seawater-aged, glass fibre-reinforced acrylic materials. Compos B Eng 2024;270:111118. https://doi.org/10.1016/j.compositesb.2023.111118.

[82] Miranda Campos B, Fontaine G, Bourbigot S, Stoclet G, Bonnet F. Matrix Composites Produced in One Step by In Situ Polymerization in TP-RTM. ACS Appl Polym Mater 2022;4:6797–802. https://doi.org/10.1021/acsapm.2c01056.

[83] Ageyeva T, Sibikin I, Kovács JG. A Review of Thermoplastic Resin Transfer Molding: Process Modeling and Simulation. Polymers 2019, Vol 11, Page 1555 2019;11:1555. https://doi.org/10.3390/POLYM11101555.

[84] Louisy E, Samyn F, Bourbigot S, Fontaine G, Bonnet F. Preparation of Glass Fabric/Poly(l-lactide) Composites by Thermoplastic Resin Transfer Molding. Polymers (Basel) 2019;11:339. https://doi.org/10.3390/polym11020339.

[85] Boros R, Sibikin I, Ageyeva T, Kovács JG. Development and Validation of a Test Mold for Thermoplastic Resin Transfer Molding of Reactive PA-6. Polymers (Basel) 2020;12:976. https://doi.org/10.3390/polym12040976.

[86] Zingraff L, Michaud V, Bourban PE, Månson JAE. Resin transfer moulding of anionically polymerised polyamide 12. Compos Part A Appl Sci Manuf 2005;36:1675–86. https://doi.org/10.1016/J.COMPOSITESA.2005.03.023.

[87] Cousins DS, Suzuki Y, Murray RE, Samaniuk JR, Stebner AP. Recycling glass fiber thermoplastic composites from wind turbine blades. J Clean Prod 2019;209:1252–63. https://doi.org/10.1016/J.JCLEPRO.2018.10.286.

[88] Qin Y, Summerscales J, Graham-Jones J, Meng M, Pemberton R. Monomer Selection for In Situ Polymerization Infusion Manufacture of Natural-Fiber Reinforced Thermoplastic-Matrix Marine Composites. Polymers (Basel) 2020;12:2928. https://doi.org/10.3390/polym12122928.

[89] Arhant M, Davies P. Thermoplastic matrix composites for marine applications. Marine Composites, Elsevier; 2019, p. 31–53. https://doi.org/10.1016/B978-0-08-102264-1.00002-9.

[90] Davies P, Le Gac P-Y, Le Gall M. Influence of Sea Water Aging on the Mechanical Behaviour of Acrylic Matrix Composites. Applied Composite Materials 2017;24:97–111. https://doi.org/10.1007/s10443-016-9516-1.

[91] Amelia H. Navigating the Best Examples of 3D Printed Boats - 3Dnatives 2018. https://www.3dnatives.com/en/3d-printed-boats-300320214/# (accessed November 30, 2023).

[92] Aysha M. Thermwood 3D prints a hull mold for a 51-foot long yacht - 3Dnatives 2020. https://www.3dnatives.com/en/thermwood-3d-printed-yacht-hull-261020206/#! (accessed November 30, 2023).

[93] Sertoglu Kubi. UMaine 3D Prints Two New Large Boats for U.S. Marines, Breaking Previous World Record - Advanced Structures & Composites Center 2022. https://composites.umaine.edu/2022/04/11/umaine-3d-prints-two-new-large-boats-for-u-s-marines-breaking-previous-world-record/ (accessed November 30, 2023).

[94] Tian X, Todoroki A, Liu T, Wu L, Hou Z, Ueda M, et al. 3D Printing of Continuous Fiber Reinforced Polymer Composites: Development, Application, and Prospective. Chinese Journal of Mechanical Engineering: Additive Manufacturing Frontiers 2022;1:100016. https://doi.org/10.1016/J.CJMEAM.2022.100016.

[95] Cheng P, Peng Y, Li S, Rao Y, Le Duigou A, Wang K, et al. 3D printed continuous fiber reinforced composite lightweight structures: A review and outlook. Compos B Eng 2023;250:110450. https://doi.org/10.1016/J.COMPOSITESB.2022.110450.

[96] Zhuo P, Li S, Ashcroft IA, Jones AI. Continuous fibre composite 3D printing with pultruded carbon/PA6 commingled fibres: Processing and mechanical properties. Compos Sci Technol 2022;221:109341. https://doi.org/10.1016/J.COMPSCITECH.2022.109341.

[97] Zhang Z, Long Y, Yang Z, Fu K, Li Y. An investigation into printing pressure of 3D printed continuous carbon fiber reinforced composites. Compos Part A Appl Sci Manuf 2022;162:107162. https://doi.org/10.1016/J.COMPOSITESA.2022.107162.

[98] Amaral-Zettler LA, Zettler ER, Mincer TJ, Klaassen MA, Gallager SM. Biofouling impacts on polyethylene density and sinking in coastal waters: A macro/micro tipping point? Water Res 2021;201:117289. https://doi.org/10.1016/j.watres.2021.117289.

[99] Zenkert D. An introduction to sandwich construction. Engineering Materials Advisory Services; 1995.

[100] AIREX T92 PET foam. https://www.3accorematerials.com/en/markets-and-products/airex-foam/airex-t92-pet-foam (accessed December 13, 2023).

[101] Recycled Pet Foam Core n.d. https://local.armacell.com/fileadmin/cms/uk/products/PET.pdf (accessed December 13, 2023).

[102] Robin A, Davies P, Arhant M, Le Jeune S, Lacotte N, Morineau E, et al. Mechanical performance of sandwich materials with reduced environmental impact for marine structures Journal of Sandwich Structures & Materials, 26(2), 99-113. https://doi.org/10.1177/10996362221127975.

[103] Life Cycle Assessment Armaform® PET. www.armacell-foam-cores.com (accessed November 30, 2023).

[104] Nidaplast 8: core material for structural sandwich panels. - Sandwich panels & honeycomb. https://www.nidaplast.com/en/content/sustainable-development (accessed November 30, 2023).

[105] Le Duigou A, Deux J-M, Davies P, Baley C. PLLA/Flax Mat/Balsa Bio-Sandwich Manufacture and Mechanical Properties. Applied Composite Materials 2011;18:421–38. https://doi.org/10.1007/s10443-010-9173-8.

[106] Gil L. Cork Composites: A Review. Materials 2009;2:776–89. https://doi.org/10.3390/ma2030776.

[107] Nedelec P. Structures et matériaux composites hautes performances pour sous-marins [in french]. Proc IFREMER conference Composites, 1988, p. 293–304.

[108] Class Rules 2025 - IMOCA 2023. https://www.imoca.org/mediacenter/uploads/2025-imoca-class-rules-v3-0.pdf?version=9072096b (accessed April 3, 2024).

[109] Martin-Raget G. The runs at Defi Azimut 2023 - Full sequence 2023. https://www.youtube.com/watch?v=5YUenblyoew (accessed November 30, 2023).

[110] Mechin P-Y, Keryvin V, Grandidier J-C, Glehen D. An experimental protocol to measure the parameters affecting the compressive strength of CFRP with a fibre micro-buckling failure criterion. Compos Struct 2019;211:154–62. https://doi.org/10.1016/j.compstruct.2018.12.026.

[111] Lukaszewicz DH-JA, Ward C, Potter KD. The engineering aspects of automated prepreg layup: History, present and future. Compos B Eng 2012;43:997–1009. https://doi.org/10.1016/j.compositesb.2011.12.003.

[112] Grabow M, Keryvin V, Marchandise A, Grandidier J-C, Baley C, Guennec C Le, et al. Influence of the manufacturing process on the interlaminar tensile strength of thick unidirectional continuous epoxy/carbon fibre composites. Compos Part A 2022;154:106754. https://doi.org/10.1016/j.compositesa.2021.106754.

[113] Marchandise A, Keryvin V, Grohens Y, Le Borgne R. Influence of the lay-up and curing steps in the manufacturing process of thick laminate composites on their compressive strength. Compos Part A Appl Sci Manuf 2023;164:107302. https://doi.org/10.1016/j.compositesa.2022.107302.

[114] Coriolis Composites: The reference in Automated Fiber Placement n.d. https://www.coriolis-composites.com/ (accessed November 30, 2023).

[115] Beakou A, Cano M, Le Cam JB, Verney V. Modelling slit tape buckling during automated prepreg manufacturing: A local approach. Compos Struct 2011;93:2628–35. https://doi.org/10.1016/J.COMPSTRUCT.2011.04.030.

[116] Inside #09 - La réalisation des foils - YouTube 2022. https://www.youtube.com/watch?v=bX90O4l8JRg (accessed November 30, 2023).

[117] Byrnes TA, Dunn RJK. Boating- and Shipping-Related Environmental Impacts and Example Management Measures: A Review. J Mar Sci Eng 2020;8:908. https://doi.org/10.3390/jmse8110908.

[118] Carreño A, Lloret J. Environmental impacts of increasing leisure boating activity in Mediterranean coastal waters. Ocean Coast Manag 2021;209:105693. https://doi.org/10.1016/j.ocecoaman.2021.105693.

[119] Ukić Boljat H, Grubišić N, Slišković M. The Impact of Nautical Activities on the Environment—A Systematic Review of Research. Sustainability 2021;13:10552. https://doi.org/10.3390/su131910552.

[120] Ghosh T, Kim HC, De Kleine R, Wallington TJ, Bakshi BR. Life cycle energy and greenhouse gas emissions implications of using carbon fiber reinforced polymers in automotive components: Front subframe case study. Sustainable Materials and Technologies 2021;28:e00263. https://doi.org/10.1016/J.SUSMAT.2021.E00263.

[121] Groetsch T, Creighton C, Varley R, Kaluza A, Dér A, Cerdas F, et al. A modular LCA/LCC-modelling concept for evaluating material and process innovations in carbon fibre manufacturing. Procedia CIRP 2021;98:529–34. https://doi.org/10.1016/J.PROCIR.2021.01.146.

[122] Dér A, Dilger N, Kaluza A, Creighton C, Kara S, Varley R, et al. Modelling and analysis of the energy intensity in polyacrylonitrile (PAN) precursor and carbon fibre manufacturing. J Clean Prod 2021;303:127105. https://doi.org/10.1016/j.jclepro.2021.127105.

[123] Kaur J, Millington K, Smith S. Producing high-quality precursor polymer and fibers to achieve theoretical strength in carbon fibers: A review. J Appl Polym Sci 2016;133. https://doi.org/10.1002/app.43963.

[124] Park S-J. Carbon Fibers. vol. 210. Singapore: Springer Singapore; 2018. https://doi.org/10.1007/978-981-13-0538-2.

[125] Song YS, Youn JR, Gutowski TG. Life cycle energy analysis of fiber-reinforced composites. Compos Part A Appl Sci Manuf 2009;40:1257–65. https://doi.org/10.1016/j.compositesa.2009.05.020.

[126] Forcellese A, Marconi M, Simoncini M, Vita A. Life cycle impact assessment of different manufacturing technologies for automotive CFRP components. J Clean Prod 2020;271:122677. https://doi.org/10.1016/j.jclepro.2020.122677.

[127] 11TH Hour Racing team sustainable Design and Build Report 2021. https://www.11thhourracingteam.org/wp-content/uploads/11th-hour-racing-team-sustainable-design-build-report.pdf (accessed November 30, 2023).

[128] MarineShift360 Life Cycle Assessment tool. https://marineshift360.org/ (accessed November 30, 2023).

[129] ADEME. Répartition de l’empreinte carbone des Français – ADEME Presse [in french] 2023. https://presse.ademe.fr/2023/09/repartition-de-lempreinte-carbone-des-francais.html#:~:text=L%27estimation%20du%20niveau%20moyen,dans%20la%20consommation%20des%20m%C3%A9nages (accessed November 30, 2023).

[130] Barros B, Wilk R. The outsized carbon footprints of the super-rich. Sustainability: Science, Practice and Policy, 2021;17:316–22. https://doi.org/10.1080/15487733.2021.1949847.

[131] United Nations Framework Convention on Climate Change. Paris Agreement 2015. https://unfccc.int/process-and-meetings/the-paris-agreement

[132] Villepreux O. Sports et médias, une marche inéluctable vers la démesure [in french]. Revue Du MAUSS 2015;46:189. https://doi.org/10.3917/rdm.046.0189.

[133] International Maritime Organization. Resolution MEPC.304(72) (adopted on 13 April 2018) Initial IMO strategy on reduction of GHG emissions from ships. https://www.imo.org/en/OurWork/Environment/Pages/2023-IMO-Strategy-on-Reduction-of-GHG-Emissions-from-Ships.aspx

[134] Rehmatulla N, Parker S, Smith T, Stulgis V. Wind technologies: Opportunities and barriers to a low carbon shipping industry. Mar Policy 2017;75:217–26. https://doi.org/10.1016/J.MARPOL.2015.12.021.

[135] Cutcher N. Winds of Trade: Passage to Zero-Emission Shipping. The American Journal of Economics and Sociology 2020;79:967–79. https://doi.org/10.1111/ajes.12331.

[136] Petković M, Zubcić M, Krcum M, Pavić I. Wind Assisted Ship Propulsion Technologies – Can they Help in Emissions Reduction? Naše More 2021;68:102–9. https://doi.org/10.17818/NM/2021/2.6.

[137] Chou T, Kosmas V, Acciaro M, Renken K. A Comeback of Wind Power in Shipping: An Economic and Operational Review on the Wind-Assisted Ship Propulsion Technology. Sustainability 2021;13:1880. https://doi.org/10.3390/su13041880.

[138] Mason J, Larkin A, Bullock S, van der Kolk N, Broderick JF. Quantifying voyage optimisation with wind propulsion for short-term CO2 mitigation in shipping. Ocean Engineering 2023;289:116065. https://doi.org/10.1016/j.oceaneng.2023.116065.

[139] Eyring V, Köhler HW, Lauer A, Lemper B. Emissions from international shipping: 2. Impact of future technologies on scenarios until 2050. J Geophys Res 2005;110:17306. https://doi.org/10.1029/2004JD005620.

[140] SolidSail - Chantiers de l'Atlantique. https://chantiers-atlantique.com/references/solid-sail-aeoldrive/ (accessed November 30, 2023).

[141] NEOLINE - Transport Maritime Responsable. https://www.neoline.eu/ (accessed November 30, 2023).

[142] Hancock B. Maximum sail Power. Nomad Press. 814 N. Franklin St. Chicago, IL 60610; 2003.

[143] Spalatelu-Lazar M, Léné F, Turbé N. Modelling and optimization of sails. Comput Struct 2008;86:1486–93. https://doi.org/10.1016/j.compstruc.2007.05.028.

[144] Desmorat B, Spalatelu M, Bohé V, Léné F, Canepa R. Optimisation de la forme des sous-domaines d'une structure élastique. Application aux voiles de bateaux [in french] 2005. https://hal.science/hal-01812997v1/file/Desmorat_2005.pdf

[145] Fallow JB. America's Cup sail design. Journal of Wind Engineering and Industrial Aerodynamics 1996;63:183–92. https://doi.org/10.1016/S0167-6105(96)00075-X.

[146] Le Maître O, Souza De Cursi JE, Huberson S. Large displacement analysis for ideally flexible sails. European Journal of Mechanics - A/Solids 1998;17:619–36. https://doi.org/10.1016/S0997-7538(99)80025-4.

[147] Bohé V, Casari P, Léné F, Davies P. Comportement des matériaux à voiles de bateau [in french]. Revue Des Composites et Des Matériaux Avancés 2003;13:251–61. https://doi.org/10.3166/rcma.13.251-261.

[148] IMOCA Purpose Report 2022. https://www.imoca.org/en/sustainability/purpose-report-2022.

[149] Baley C, Lan M, Davies P, Cartié D. Porosity in Ocean Racing Yacht Composites: a Review. Applied Composite Materials 2015;22:13–28. https://doi.org/10.1007/s10443-014-9393-4.

[150] Arteiro A, Furtado C, Catalanotti G, Linde P, Camanho PP. Thin-ply polymer composite materials: A review. Compos Part A Appl Sci Manuf 2020;132:105777. https://doi.org/10.1016/J.COMPOSITESA.2020.105777.

[151] Grandidier J-C, Casari P, Jochum C. A fibre direction compressive failure criterion for long fibre laminates at ply scale, including stacking sequence and laminate thickness effects. Compos Struct 2012;94:3799–806. https://doi.org/10.1016/j.compstruct.2012.06.013.

[152] Rodini BT, Eisenmann JR. An Analytical and Experimental Investigation of Edge Delamination in Composite Laminates. Fibrous Composites in Structural Design 1980:441–57. https://doi.org/10.1007/978-1-4684-1033-4_25.

[153] Yokozeki T, Kuroda A, Yoshimura A, Ogasawara T, Aoki T. Damage characterization in thin-ply composite laminates under out-of-plane transverse loadings. Compos Struct 2010;93:49–57. https://doi.org/10.1016/J.COMPSTRUCT.2010.06.016.

[154] Arteiro A, Catalanotti G, Xavier J, Camanho PP. Notched response of non-crimp fabric thin-ply laminates. Compos Sci Technol 2013;79:97–114. https://doi.org/10.1016/J.COMPSCITECH.2013.02.001.

[155] Yokozeki T, Aoki Y, Ogasawara T. Experimental characterization of strength and damage resistance properties of thin-ply carbon fiber/toughened epoxy laminates. Compos Struct 2008;82:382–9. https://doi.org/10.1016/J.COMPSTRUCT.2007.01.015.

[156] Mencattelli L, Pinho ST. Realising bio-inspired impact damage-tolerant thin-ply CFRP Bouligand structures via promoting diffused sub-critical helicoidal damage. Compos Sci Technol 2019;182:107684. https://doi.org/10.1016/J.COMPSCITECH.2019.107684.

[157] Sihn S, Kim RY, Kawabe K, Tsai SW. Experimental studies of thin-ply laminated composites. Compos Sci Technol 2007;67:996–1008. https://doi.org/10.1016/J.COMPSCITECH.2006.06.008.

[158] Galos J. Thin-ply composite laminates: a review. Compos Struct 2020;236:111920. https://doi.org/10.1016/J.COMPSTRUCT.2020.111920.

[159] IMOCA website. https://www.imoca.org/fr (accessed December 1, 2023).

[160] Hillairet D. Existe-t-il un milieu innovateur dans l'industrie du sport ? [in french]. Innovations 2002;16:71–100. https://doi.org/10.3917/INNO.016.0071.

[161] Technical Summary. Climate Change 2021 – The Physical Science Basis, Cambridge University Press; 2023, p. 35–144. https://doi.org/10.1017/9781009157896.002.

[162] Genzling C. Sports et sciences en compétition [in french]. Revue Autrement 1992:11–27.

[163] Gorman Ed. The IMOCA Green Sail Rule: A successful first season but now it's time to increase its scope and tighten it 2023. https://www.imoca.org/en/news/news/the-imoca-green-sail-rule-a-successful-first-season-but-now-its-time-to-increase-its-scope-and-tighten-it (accessed November 30, 2023).

[164] Ocean Fifty Class Rules, 2021. https://oceanfifty.com/wp-content/uploads/2021/05/OCEAN-FIFTY-REGLES-DE-CLASSE-2021-DEF.pdf (accessed November 30, 2023).

[165] Class Mini Rules, 2023. https://www.classemini.com/modules/kameleon/upload/12023-textesofficiels-officialtextsincludingamendmentn1.pdf (accessed November 30, 2023).

[166] Bouty I, Drucker-Godard C. Emergence de l'agir collectif dans la course à la voile : rythme et coordination [in french]. Emergence de l'agir Collectif Dans La Course à La Voile : Rythme et Coordination 2011. https://www.cairn.info/revue-management-et-avenir-2011-1-page-435.htm

[167] Rani M, Choudhary P, Krishnan V, Zafar S. A review on recycling and reuse methods for carbon fiber/glass fiber composites waste from wind turbine blades. Compos B Eng 2021;215:108768. https://doi.org/10.1016/J.COMPOSITESB.2021.108768.

[168] Groetsch T, Maghe M, Creighton C, Varley RJ. Environmental, property and cost impact analysis of carbon fibre at increasing rates of production. J Clean Prod 2023;382:135292. https://doi.org/10.1016/J.JCLEPRO.2022.135292.

[169] Obasa VD, Olanrewaju OA, Gbenebor OP, Ochulor EF, Odili CC, Abiodun YO, et al. A Review on Lignin-Based Carbon Fibres for Carbon Footprint Reduction. Atmosphere (Basel) 2022;13:1605. https://doi.org/10.3390/atmos13101605.

[170] Soulis S, Konstantopoulos G, Koumoulos EP, Charitidis CA. Impact of Alternative Stabilization Strategies for the Production of PAN-Based Carbon Fibers with High Performance. Fibers 2020, Vol 8, Page 33 2020;8:33. https://doi.org/10.3390/FIB8060033.

[171] Jin S, Guo C, Lu Y, Zhang R, Wang Z, Jin M. Comparison of microwave and conventional heating methods in carbonization of polyacrylonitrile-based stabilized fibers at different temperature measured by an in-situ process temperature control ring. Polym Degrad Stab 2017;140:32–41. https://doi.org/10.1016/j.polymdegradstab.2017.04.002.

[172] Gardiner G. Mitsui Chemicals, Microwave Chemical install demonstration facility for eco-friendly carbon fiber | CompositesWorld 2023. https://www.compositesworld.com/news/mitsui-chemicals-microwave-chemical-install-demonstration-facility-for-eco-friendly-carbon-fiber (accessed November 30, 2023).

[173] La Rosa AD, Blanco I, Banatao DR, Pastine SJ, Björklund A, Cicala G. Innovative Chemical Process for Recycling Thermosets Cured with Recyclamines® by Converting Bio-Epoxy Composites in Reusable Thermoplastic—An LCA Study. Materials 2018, Vol 11, Page 353 2018;11:353. https://doi.org/10.3390/MA11030353.

[174] Jeong Y-K, Lee P, Nam S, Lee DK, Shin J-G. Development of the Methodology for Environmental Impact of Composite Boats Manufacturing Process. Procedia CIRP 2015;29:456–61. https://doi.org/10.1016/j.procir.2015.02.074.

[175] Nam S, Lee DK, Jeong Y-K, Lee P, Shin J-G. Environmental impact assessment of composite small craft manufacturing using the generic work breakdown structure. International Journal of Precision Engineering and Manufacturing-Green Technology 2016;3:261–72. https://doi.org/10.1007/s40684-016-0034-2.

[176] Vita A, Castorani V, Germani M, Marconi M. Comparative life cycle assessment and cost analysis of autoclave and pressure bag molding for producing CFRP components. The International Journal of Advanced Manufacturing Technology 2019;105:1967–82. https://doi.org/10.1007/s00170-019-04384-9.

[177] Vita A, Castorani V, Germani M, Marconi M. Comparative life cycle assessment of low-pressure RTM, compression RTM and high-pressure RTM manufacturing processes to produce CFRP car hoods. Procedia CIRP 2019;80:352–7. https://doi.org/10.1016/j.procir.2019.01.109.

[178] Al-Lami A, Hilmer P, Sinapius M. Eco-efficiency assessment of manufacturing carbon fiber reinforced polymers (CFRP) in aerospace industry. Aerosp Sci Technol 2018;79:669–78. https://doi.org/10.1016/j.ast.2018.06.020.

[179] Chen J, Wang J, Ni A. Recycling and reuse of composite materials for wind turbine blades: An overview. Journal of Reinforced Plastics and Composites 2019;38:567–77. https://doi.org/10.1177/0731684419833470.

[180] Zhang J, Chevali VS, Wang H, Wang CH. Current status of carbon fibre and carbon fibre composites recycling. Compos B Eng 2020;193:108053. https://doi.org/10.1016/J.COMPOSITESB.2020.108053.

[181] Salas A, Berrio ME, Martel S, Díaz-Gómez A, Palacio DA, Tuninetti V, et al. Towards recycling of waste carbon fiber: Strength, morphology and structural features of recovered carbon fibers. Waste Management 2023;165:59–69. https://doi.org/10.1016/J.WASMAN.2023.04.017.

[182] Pillain B, Loubet P, Pestalozzi F, Woidasky J, Erriguible A, Aymonier C, et al. Positioning supercritical solvolysis among innovative recycling and current waste management scenarios for carbon fiber reinforced plastics thanks to comparative life cycle assessment. J Supercrit Fluids 2019;154:104607. https://doi.org/10.1016/J.SUPFLU.2019.104607.

[183] Meng F, McKechnie J, Turner TA, Pickering SJ. Energy and environmental assessment and reuse of fluidised bed recycled carbon fibres. Compos Part A Appl Sci Manuf 2017;100:206–14. https://doi.org/10.1016/J.COMPOSITESA.2017.05.008.

[184] Kawajiri K, Kobayashi M. Cradle-to-Gate life cycle assessment of recycling processes for carbon fibers: A case study of ex-ante life cycle assessment for commercially feasible pyrolysis and solvolysis approaches. J Clean Prod 2022;378:134581. https://doi.org/10.1016/J.JCLEPRO.2022.134581.

[185] Longana ML, Yu HN, Potter KD, Wisnom MR, Hamerton I. The HipERDIF (High performance discontinuous fibres) technology for the manufacturing of pseudo-ductile quasi-isotropic aligned discontinuous fibre composites. Proc. 18th European Conference on Composite Materials, ECCM 2018 - Athens, Greece.

[186] Pakdel E, Kashi S, Varley R, Wang X. Recent progress in recycling carbon fibre reinforced composites and dry carbon fibre wastes. Resour Conserv Recycl 2021;166:105340. https://doi.org/10.1016/J.RESCONREC.2020.105340.

[187] Mantaux O, Max A, Gillet D, Cazaurang G, Lacoste E, Gillet A. Réalisation de pièces structurales de technicité croissante pour le nautisme de compétition à partir de fibres de carbone recyclées [in french] 2019, Proc 21st Journées Nationales sur les Composites, ENSAM Bordeaux July 2019.

[188] Davies P, Dumergue N, Arhant M, Nicolas E, Paboeuf S, Mayorga P. Material and structural testing to improve composite tidal turbine blade reliability. International Marine Energy Journal 2022;5:57–65. https://doi.org/10.36688/imej.5.57-65.

[189] Grogan DM, Leen SB, Kennedy CR, Ó Brádaigh CM. Design of composite tidal turbine blades. Renew Energy 2013;57:151–62. https://doi.org/10.1016/j.renene.2013.01.021.

[190] Weitsman YJ. Fluid Effects in Polymers and Polymeric Composites, 2012. https://doi.org/10.1007/978-1-4614-1059-1.

[191] Colin X, Verdu J. Humid ageing of organic matrix composites. Solid Mechanics and Its Applications 2014;208:47–114. https://doi.org/10.1007/978-94-007-7417-9_3/COVER.

[192] Davies P. Towards More Representative Accelerated Aging of Marine Composites. Advances in Thick Section Composite and Sandwich Structures, Springer International Publishing; 2020, p. 507–27. https://doi.org/10.1007/978-3-030-31065-3_17.

[193] Dezulier Q, Clement A, Davies P, Jacquemin F, Arhant M, Flageul B. Characterization and modelling of the hygro-viscoelastic behaviour of polymer-based composites used in marine

environment. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 2023;381. https://doi.org/10.1098/rsta.2021.0221.

[194] Microplastics - European Commission https://environment.ec.europa.eu/topics/plastics/microplastics_en (accessed December 18, 2023).

[195] Wright SL, Thompson RC, Galloway TS. The physical impacts of microplastics on marine organisms: A review. Environmental Pollution 2013;178:483–92. https://doi.org/10.1016/J.ENVPOL.2013.02.031.

[196] Andrady AL. Microplastics in the marine environment. Mar Pollut Bull 2011;62:1596–605. https://doi.org/10.1016/J.MARPOLBUL.2011.05.030.

[197] El Hawary O, Boccarusso L, Ansell MP, Durante M, Pinto F. An Overview of Natural Fiber Composites for Marine Applications. J Mar Sci Eng 2023;11:1076. https://doi.org/10.3390/jmse11051076.

[198] Crupi V, Epasto G, Napolitano F, Palomba G, Papa I, Russo P. Green Composites for Maritime Engineering: A Review. J Mar Sci Eng 2023;11:599. https://doi.org/10.3390/jmse11030599.

[199] Bourmaud A, Beaugrand J, Shah DU, Placet V, Baley C. Towards the design of high-performance plant fibre composites. Prog Mater Sci 2018;97:347–408. https://doi.org/10.1016/J.PMATSCI.2018.05.005.

[200] Baley C, Bourmaud A. Multiscale Structure of Plant Fibers. Encyclopedia of Materials: Composites, Elsevier; 2021, p. 117–34. https://doi.org/10.1016/B978-0-12-819724-0.00112-9.

[201] Baley C, Gomina M, Breard J, Bourmaud A, Drapier S, Ferreira M, et al. Specific features of flax fibres used to manufacture composite materials. International Journal of Material Forming 2019;12:1023–52. https://doi.org/10.1007/s12289-018-1455-y.

[202] Baley C, Gomina M, Breard J, Bourmaud A, Davies P. Variability of mechanical properties of flax fibres for composite reinforcement. A review. Ind Crops Prod 2020;145:111984. https://doi.org/10.1016/j.indcrop.2019.111984.

[203] Bourmaud A, Baley C. Investigations on the recycling of hemp and sisal fibre reinforced polypropylene composites. Polym Degrad Stab 2007;92:1034–45. https://doi.org/10.1016/J.POLYMDEGRADSTAB.2007.02.018.

[204] Bourmaud A, Baley C. Rigidity analysis of polypropylene/vegetal fibre composites after recycling. Polym Degrad Stab 2009;94:297–305. https://doi.org/10.1016/J.POLYMDEGRADSTAB.2008.12.010.

[205] Gourier C, Bourmaud A, Le Duigou A, Baley C. Influence of PA11 and PP thermoplastic polymers on recycling stability of unidirectional flax fibre reinforced biocomposites. Polym Degrad Stab 2017;136:1–9. https://doi.org/10.1016/J.POLYMDEGRADSTAB.2016.12.003.

[206] Bodros E, Pillin I, Montrelay N, Baley C. Could biopolymers reinforced by randomly scattered flax fibre be used in structural applications? Compos Sci Technol 2007;67:462–70. https://doi.org/10.1016/J.COMPSCITECH.2006.08.024.

[207] NF EN ISO 14855-1: Determination of the ultimate aerobic biodegradability of plastic materials under controlled composting conditions - Method by analysis of evolved carbon dioxide - Part 1 : general method. 2013.

[208] NF EN ISO 14855-2: Determination of the ultimate aerobic biodegradability of plastic materials under controlled composting conditions Method by analysis of evolved carbon dioxide Part 2: Gravimetric measurement of carbon dioxide evolved in a laboratory-scale test. 2018.

[209] Pantaloni D, Shah D, Baley C, Bourmaud A. Monitoring of mechanical performances of flax non-woven biocomposites during a home compost degradation. Polym Degrad Stab 2020;177:109166. https://doi.org/10.1016/j.polymdegradstab.2020.109166.

[210] Fiore V, Scalici T, Di Bella G, Valenza A. A review on basalt fibre and its composites. Compos B Eng 2015;74:74–94. https://doi.org/10.1016/j.compositesb.2014.12.034.

[211] Jamshaid H, Mishra R. A green material from rock: basalt fiber – a review. The Journal of The Textile Institute 2016;107:923–37. https://doi.org/10.1080/00405000.2015.1071940.

[212] Liu H, Yu Y, Liu Y, Zhang M, Li L, Ma L, et al. A Review on Basalt Fiber Composites and Their Applications in Clean Energy Sector and Power Grids. Polymers (Basel) 2022;14:2376. https://doi.org/10.3390/polym14122376.

[213] Wei B, Cao H, Song S. Degradation of basalt fibre and glass fibre/epoxy resin composites in seawater. Corros Sci 2011;53:426–31. https://doi.org/10.1016/J.CORSCI.2010.09.053.

[214] Davies P, Le Gac PY, Le Gall M, Arhant M. Marine Ageing Behaviour of New Environmentally Friendly Composites. In Durability of Composites in a Marine Environment 2, ed Davies P, Rajapakse YD, Springer 2018;225–37. https://link.springer.com/book/10.1007/978-3-319-65145-3

[215] Fořt J, Kočí J, Černý R. Environmental Efficiency Aspects of Basalt Fibers Reinforcement in Concrete Mixtures. Energies 2021, Vol 14, Page 7736 2021;14:7736. https://doi.org/10.3390/EN14227736.

[216] Life Cycle Assessment (LCA) of Basalt Fibers versus Glass Fibers | basaltfiberworld n.d. https://basaltfiberworld.wordpress.com/scientifical-research/life-cycle-assessment-lca-of-basalt-fibers-versus-glass-fibers/ (accessed December 15, 2023).

[217] Lucas N, Bienaime C, Belloy C, Queneudec M, Silvestre F, Nava-Saucedo J-E. Polymer biodegradation: Mechanisms and estimation techniques – A review. Chemosphere 2008;73:429–42. https://doi.org/10.1016/j.chemosphere.2008.06.064.

[218] Harrison JP, Boardman C, O'Callaghan K, Delort A-M, Song J. Biodegradability standards for carrier bags and plastic films in aquatic environments: a critical review. R Soc Open Sci 2018;5:171792. https://doi.org/10.1098/rsos.171792.

[219] Pires JRA, Souza VGL, Fuciños P, Pastrana L, Fernando AL. Methodologies to Assess the Biodegradability of Bio-Based Polymers—Current Knowledge and Existing Gaps. Polymers (Basel) 2022;14:1359. https://doi.org/10.3390/polym14071359.

[220] Albright VC, Chai Y. Knowledge Gaps in Polymer Biodegradation Research. Environ Sci Technol 2021;55:11476–88. https://doi.org/10.1021/acs.est.1c00994.

[221] Lim BKH, Thian ES. Biodegradation of polymers in managing plastic waste - A review. Science of The Total Environment 2022;813:151880. https://doi.org/10.1016/j.scitotenv.2021.151880.

[222] NF EN ISO 18830:2016: Determination of aerobic biodegradation of non-floating plastic materials in a seawater/sandy sediment interface. 2016.

[223] NF EN ISO 19679:2020: Determination of aerobic biodegradation of non-floating plastic materials in a seawater/sediment interface. 2020.

[224] ASTM D6691-17. ASTM D6691-17: Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials in the Marine Environment by a Defined Microbial Consortium or Natural Sea Water Inoculum. 2017.

[225] NF EN ISO 22766:2020: Determination of the degree of disintegration of plastic materials in marine habitats under real field conditions. 2020.

[226] Van Rossum T. Marine biodegradability review of plastics. Water Cycle 2021;2:38–43. https://doi.org/10.1016/j.watcyc.2021.06.001.

[227] Haider TP, Völker C, Kramm J, Landfester K, Wurm FR. Plastics of the Future? The Impact of Biodegradable Polymers on the Environment and on Society. Angewandte Chemie International Edition 2019;58:50–62. https://doi.org/10.1002/anie.201805766.

[228] Lott C, Eich A, Unger B, Makarow D, Battagliarin G, Schlegel K, et al. Field and mesocosm methods to test biodegradable plastic film under marine conditions. PLoS One 2020;15:e0236579. https://doi.org/10.1371/journal.pone.0236579.

[229] Briassoulis D, Pikasi A, Papardaki NG, Mistriotis A. Aerobic biodegradation of bio-based plastics in the seawater/sediment interface (sublittoral) marine environment of the coastal zone – Test method under controlled laboratory conditions. Science of The Total Environment 2020;722:137748. https://doi.org/10.1016/j.scitotenv.2020.137748.

[230] Cheng J, Eyheraguibel B, Jacquin J, Pujo-Pay M, Conan P, Barbe V, et al. Biodegradability under marine conditions of bio-based and petroleum-based polymers as substitutes of conventional microparticles. Polym Degrad Stab 2022;206:110159. https://doi.org/10.1016/j.polymdegradstab.2022.110159.

[231] Romano C, Nunes-Jorge A, Le Bris N, Rouse GW, Martin D, Borowski C. Wooden Stepping Stones: Diversity and Biogeography of Deep-Sea Wood Boring Xylophagaidae (Mollusca: Bivalvia) in the North-East Atlantic Ocean, With the Description of a New Genus. Front Mar Sci 2020;7. https://doi.org/10.3389/fmars.2020.579959.

[232] Nishimoto A, Haga T, Asakura A, Shirayama Y. An experimental approach for understanding the process of wood fragmentation by marine wood borers in shallow temperate waters. Mar Ecol Prog Ser 2015;538:53–65. https://doi.org/10.3354/meps11454.

[233] Björdal CG, Nilsson T. Reburial of shipwrecks in marine sediments: a long-term study on wood degradation. J Archaeol Sci 2008;35:862–72. https://doi.org/10.1016/j.jas.2007.06.005.

[234] Chen H. Biodegradable plastics in the marine environment: a potential source of risk? Water Emerging Contaminants & Nanoplastics 2022;1:16. https://doi.org/10.20517/wecn.2022.11.

[235] Lott C, Eich A, Makarow D, Unger B, van Eekert M, Schuman E, et al. Half-Life of Biodegradable Plastics in the Marine Environment Depends on Material, Habitat, and Climate Zone. Front Mar Sci 2021;8. https://doi.org/10.3389/fmars.2021.662074.

[236] Nagamine R, Kobayashi K, Kusumi R, Wada M. Cellulose fiber biodegradation in natural waters: river water, brackish water, and seawater. Cellulose 2022;29:2917–26. https://doi.org/10.1007/s10570-021-04349-w.

[237] Pommier R, Grimaud G, Prinçaud M, Perry N, Sonnemann G. Comparative environmental life cycle assessment of materials in wooden boat ecodesign. Int J Life Cycle Assess 2016;21:265–75. https://doi.org/10.1007/s11367-015-1009-1.

[238] Goldhahn C, Cabane E, Chanana M. Sustainability in wood materials science: an opinion about current material development techniques and the end of lifetime perspectives. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 2021;379. https://doi.org/10.1098/rsta.2020.0339.

[239] Moulia B. Plant biomechanics and mechanobiology are convergent paths to flourishing interdisciplinary research. J Exp Bot, 2013;64:4617–33. https://doi.org/10.1093/jxb/ert320.

[240] Biddington NL. The effects of mechanically-induced stress in plants-a review. Plant Growth Regul 1986;4:103–23. https://doi.org/10.1007/BF00025193.

[241] Hayes G, Laurel M, MacKinnon D, Zhao T, Houck HA, Becer CR. Polymers without Petrochemicals: Sustainable Routes to Conventional Monomers. Chem Rev 2023;123:2609–734. https://doi.org/10.1021/acs.chemrev.2c00354.

[242] Andrews D. Creative Ship Design. Proceedings RINA meeting Newcastle: Vol 123. 1981. https://trid.trb.org/view/404442

[243] Pawling R, Percival V, Andrews D. A Study into the Validity of the Ship Design Spiral in Early Stage Ship Design. Journal of Ship Production and Design 2017;33:81–100. https://doi.org/10.5957/JSPD.33.2.160008.

[244] Presles D, Paulet D. Naval Architecture: Knowledge and Practice [In French]. Editions de la Villette. Paris: 2005.

[245] Budynas RG, Nisbett JK, Shigley's Mechanical Engineering Design, 11th Edition. McGraw-Hill 2020. ISBN 978-0-07-339820-4

[246] Ugural AC. Introduction. Mechanical Engineering Design, Boca Raton: CRC Press; 2022, p. 3-39. https://doi.org/10.1201/9781003251378-2.

[247] ISO 14067:2018 - Greenhouse gases. Carbon footprint of products. Requirements and guidelines for quantification. https://www.iso.org/fr/standard/71206.html (accessed March 28, 2024).

[248] NF EN ISO 14040 : 2006 Environmental Management - Life Cycle Assessment https://www.intertekinform.com/en-gb/standards/nf-en-iso-14040-2006-83240_saig_afnor_afnor_175160/ (accessed March 28, 2024).

[249] Hermansson F, Janssen M, Svanström M. Prospective study of lignin-based and recycled carbon fibers in composites through meta-analysis of life cycle assessments. J Clean Prod 2019;223:946–56. https://doi.org/10.1016/J.JCLEPRO.2019.03.022.

[250] Ostermann M, Grenz J, Triebus M, Cerdas F, Marten T, Tröster T, et al. Integrating Prospective Scenarios in Life Cycle Engineering: Case Study of Lightweight Structures. Energies (Basel) 2023;16:3371. https://doi.org/10.3390/en16083371.

[251] Thonemann N, Schulte A, Maga D. How to Conduct Prospective Life Cycle Assessment for Emerging Technologies? A Systematic Review and Methodological Guidance. Sustainability 2020;12:1192. https://doi.org/10.3390/su12031192.

[252] Stenius I, Rosén A, Kuttenkeuler J. On structural design of energy efficient small high-speed craft. Marine Structures 2011;24:43–59. https://doi.org/10.1016/j.marstruc.2011.01.001.

[253] Perčić M, Frković L, Pukšec T, Ćosić B, Li OL, Vladimir N. Life-cycle assessment and life-cycle cost assessment of power batteries for all-electric vessels for short-sea navigation. Energy 2022;251:123895. https://doi.org/10.1016/j.energy.2022.123895.

[254] van Gelder P, Klaassen P, Taebi B, Walhout B, van Ommen R, van de Poel I, et al. Safe-by-Design in Engineering: An Overview and Comparative Analysis of Engineering Disciplines. Int J Environ Res Public Health 2021;18:6329. https://doi.org/10.3390/ijerph18126329.

[255] Subramanian V, Peijnenburg WJGM, Vijver MG, Blanco CF, Cucurachi S, Guinée JB. Approaches to implement safe by design in early product design through combining risk assessment and Life Cycle Assessment. Chemosphere 2023;311:137080. https://doi.org/10.1016/j.chemosphere.2022.137080.

[256] Martínez-Vázquez RM, Milán-García J, De Pablo Valenciano J. Challenges and opportunities for the future of recreational boat scrapping: The Spanish case. Mar Pollut Bull 2022;178:113557. https://doi.org/10.1016/j.marpolbul.2022.113557.

[257] Bathô - Fabricant d’hébergements insolites [in french] https://www.batho.fr/ (accessed December 13, 2023).

[258] Innovating to bring boat experiences for everyone - Groupe Beneteau. https://www.beneteau-group.com/en/innovating-to-bring-boat-experiences-to-everyone/ (accessed December 4, 2023).

[259] Fratzl P. Introduction: Sustainable Materials. Chem Rev 2023;123:1841–2. https://doi.org/10.1021/acs.chemrev.3c00091.

[260] Eder M, Amini S, Fratzl P. Biological composites—complex structures for functional diversity. Science (1979) 2018;362:543–7. https://doi.org/10.1126/science.aat8297.

[261] XP X42-502: Biomimicry – Integration of biomimetics in ecodesign approaches. 2017.

[262] Ehrlich H. Marine Biological Materials of Invertebrate Origin. vol. 13. Springer International Publishing; 2019. https://doi.org/10.1007/978-3-319-92483-0.

[263] Ehrlich H. Biological Materials of Marine Origin. vol. 1. Dordrecht: Springer Netherlands; 2010. https://doi.org/10.1007/978-90-481-9130-7.

Figure 1 : Illustration of A) strong and B) weak sustainability

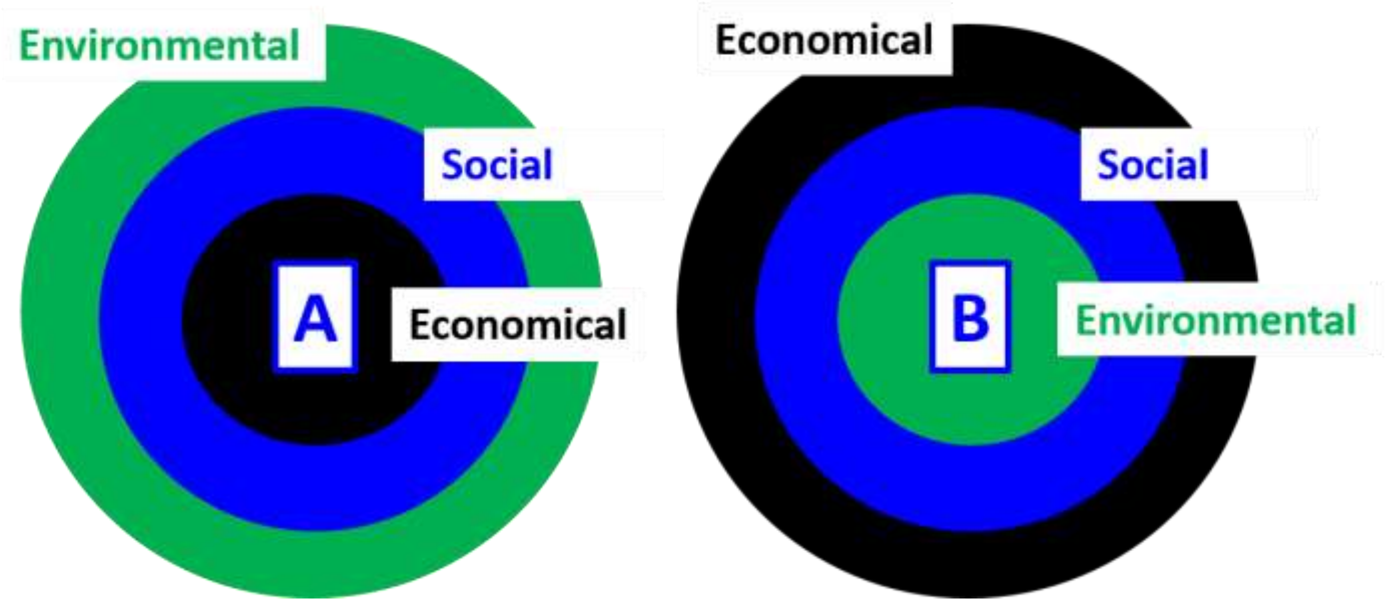

Figure 2 : Factors to consider in material selection for boat and ship hulls

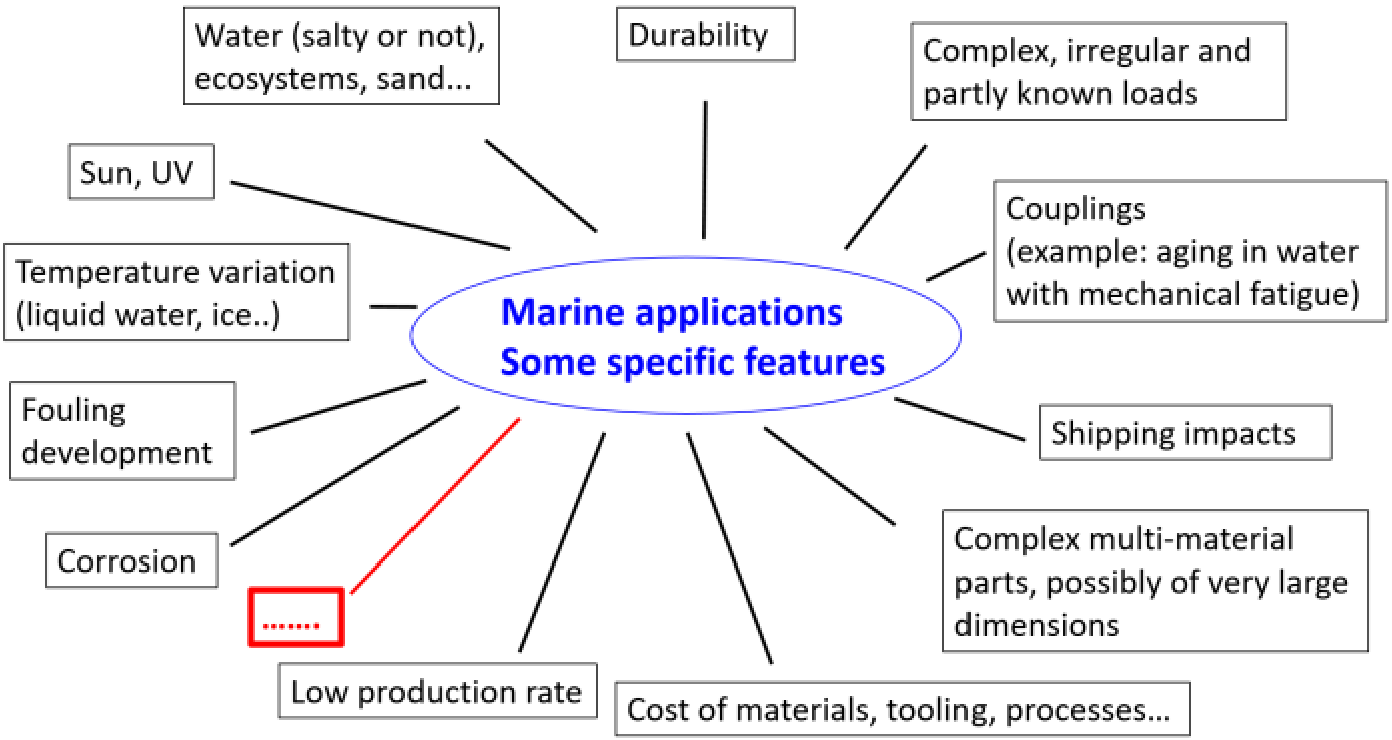

Figure 3 : Knock-on effect in mass reduction for a motorboat. (adapted from D. Gay [6])

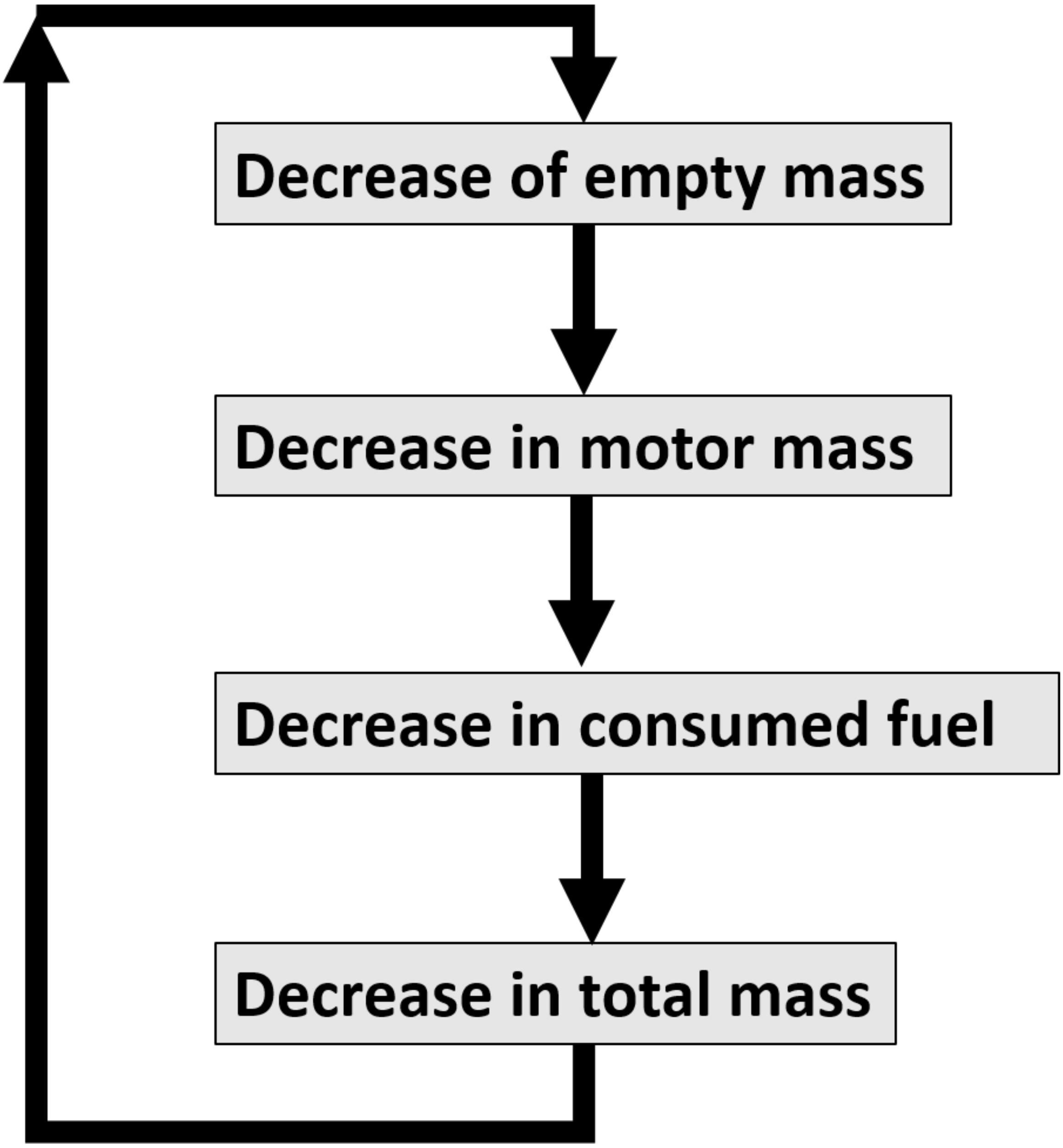

Figure 4 : Changes to material selection philosophy

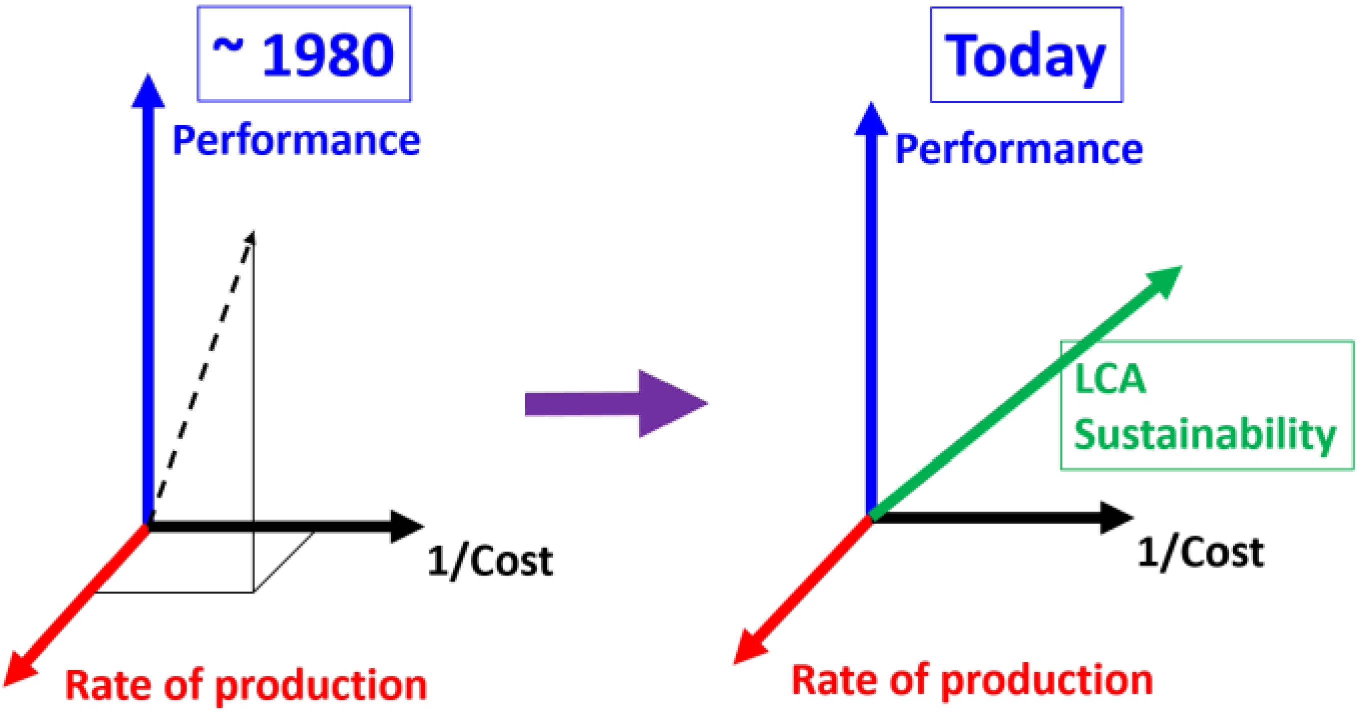

Figure 5. A hierarchical procedure on two levels and to extend the selection criteria.

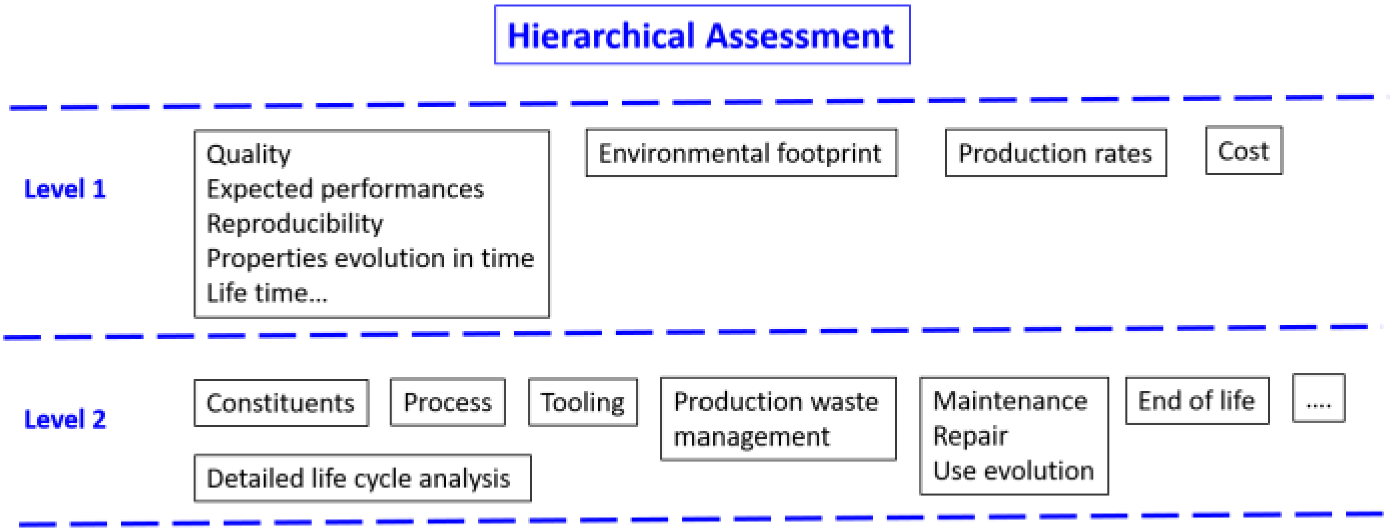

Figure 6 : Small pleasure boats abandoned on the French coast.

Figure 7. Wooden boat graveyard (Kerhervy , Lanester, France)

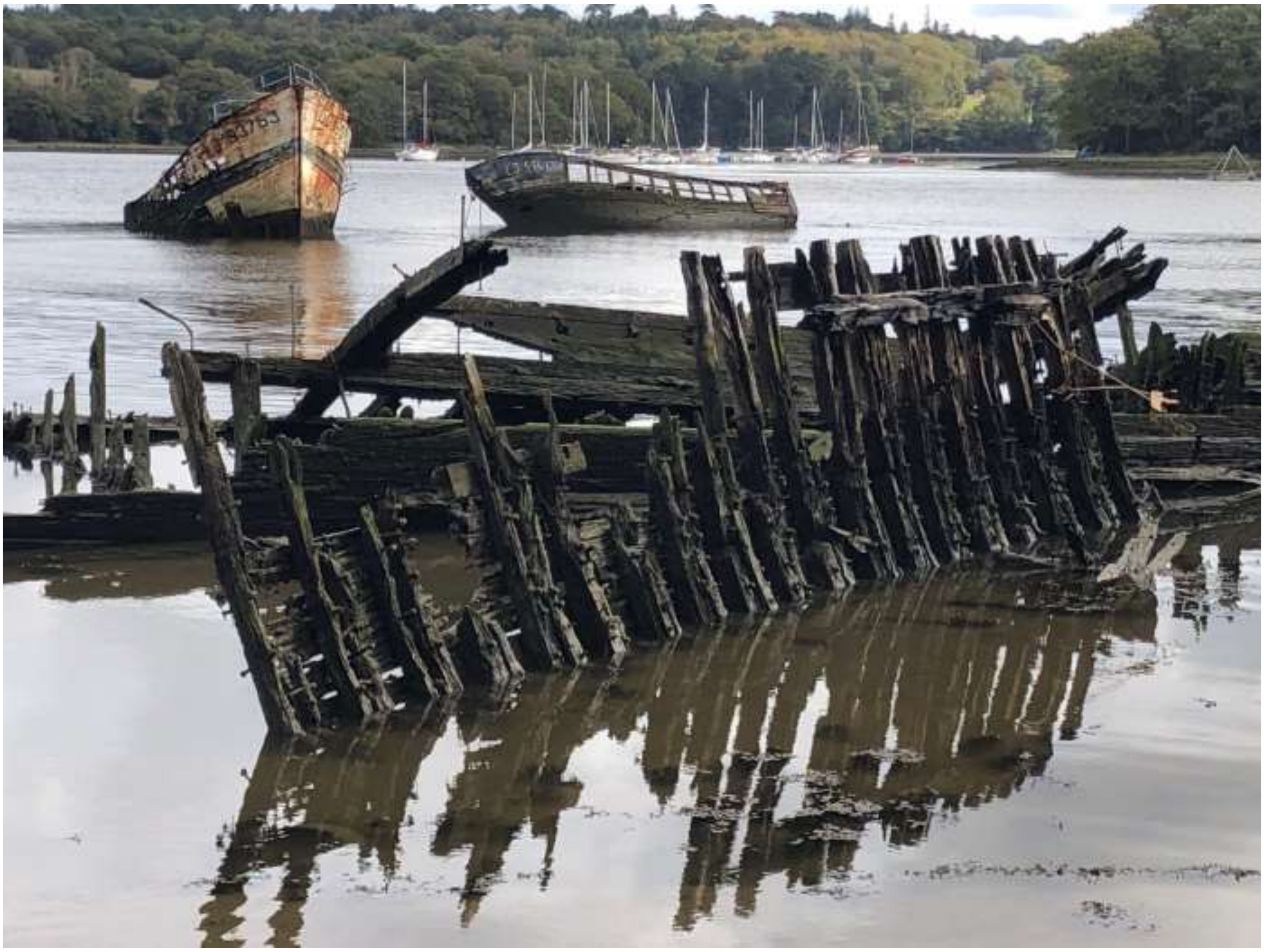

Figure 8: Possibilities of recycling

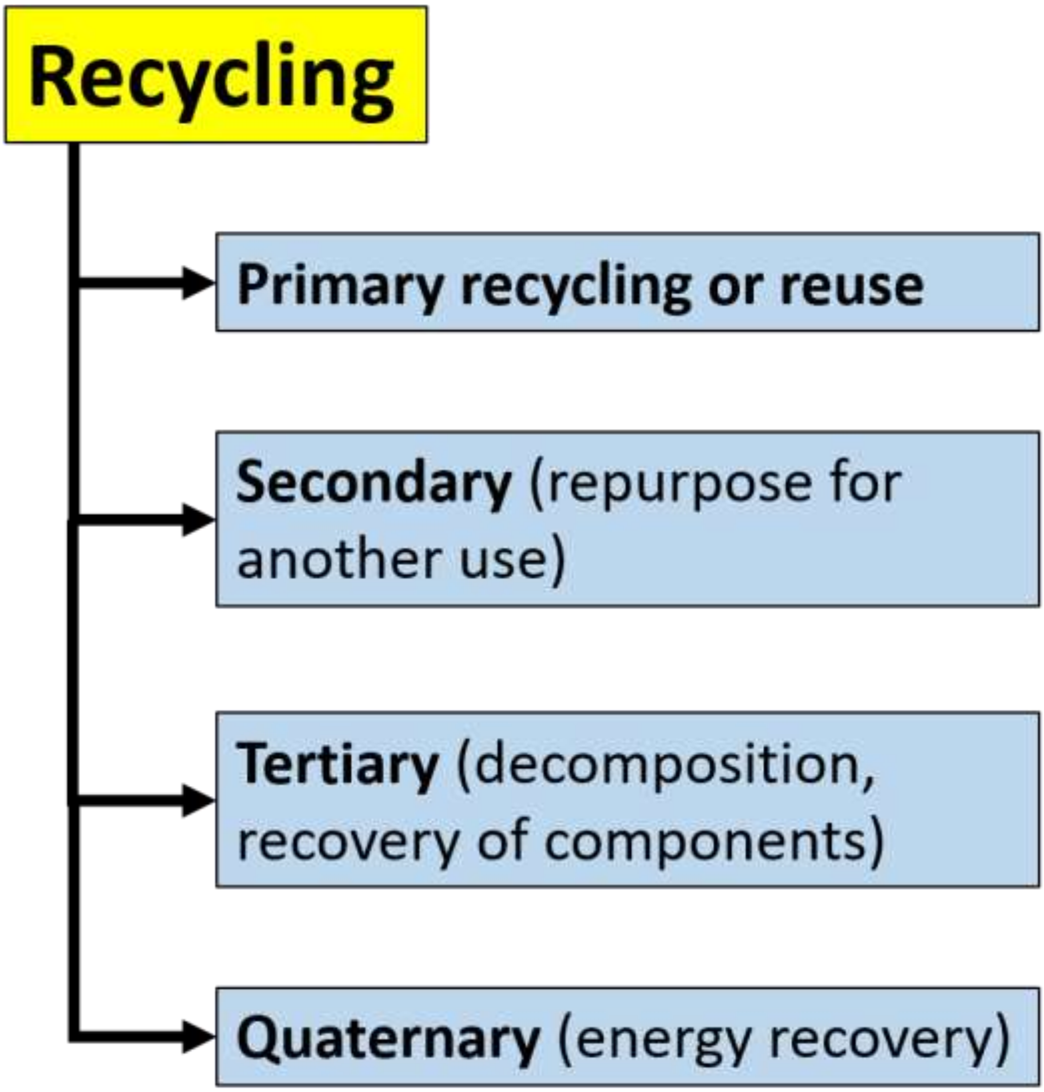

Figure 9 : Flax/PLA canoe (length 4.40 m), manufacture by vacuum forming then autoclave, using film stacking, NAVECOMAT project [61]

Figure 10 :

a) Glass/PP catamaran, 4.60 m long (Twincat 15). The absence of an external coating reveals the reinforcement

(b) photo taken on rudder blade, the matrix contains a black pigment which highlights the fibres.

Figure 11 : Composite autonomous profiler for deep sea measurements [74]

Figure 12: Imoca Paprec Arkea 2023 ‘flying’ on foils during *Défi Azimut* trials in 2023 (Crédit ©JM Liot / Défi Azimut)

Figure 13. Diagram showing the loading conditions for an IMOCA navigating on foils:

a /Critical zones (hull connection and elbow).

In green : Foil deformed under normal conditions

In red : Foil deformed under critical conditions (lift reversal)

b / Opening of L-section resulting in transverse tension and risk of delamination (adapted from D. Gay [10])

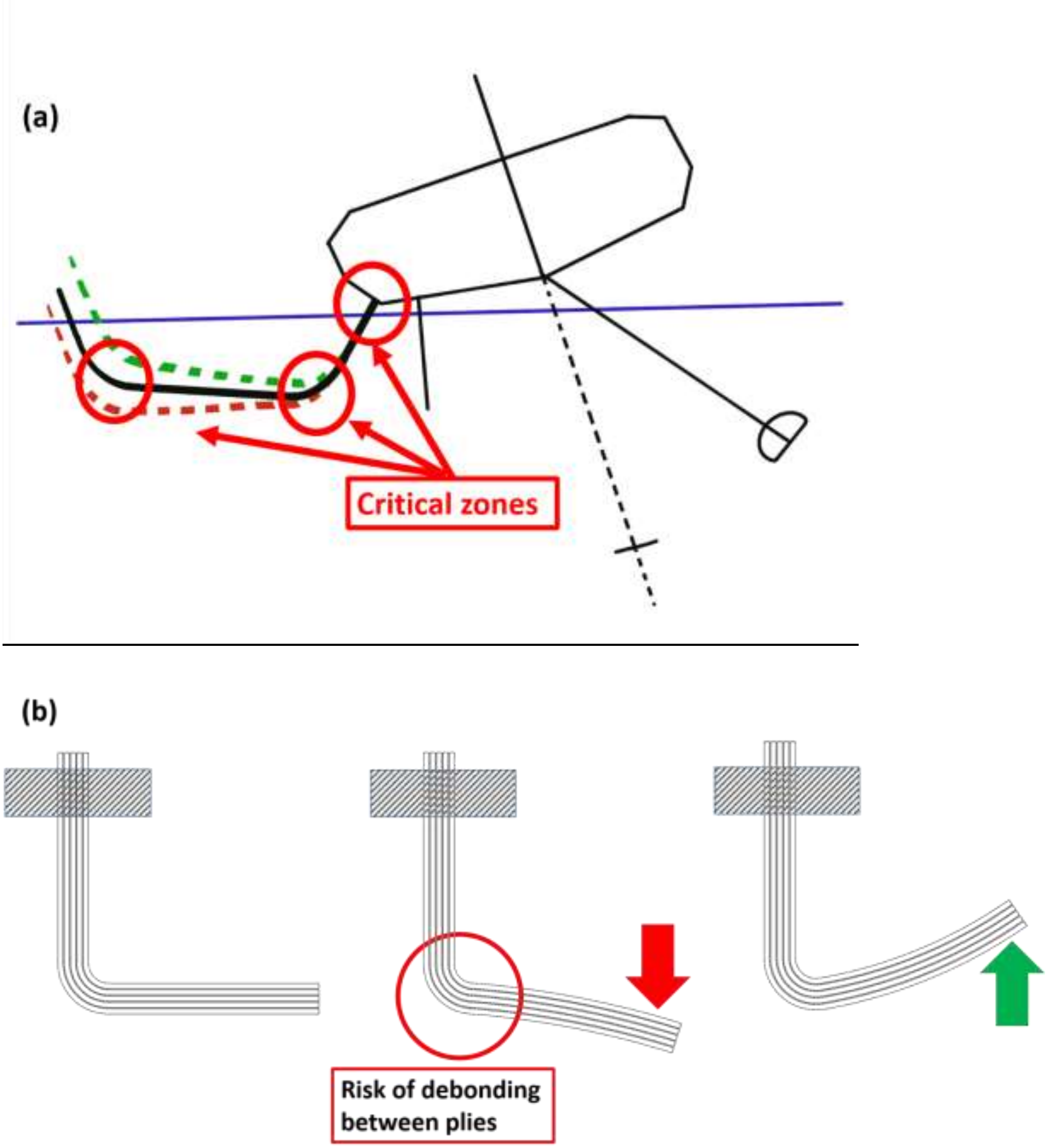

Figure 14: Foil of a catamaran (GC 32) during manufacture (2017). The shaft (lower) and the tip (upper) are composites which are joined to a metallic elbow (stainless steel or titanium alloy) which will then be covered by composite. (Photo Avel Robotics)

Figure 15: Foil manufacture:

A / Lay-up of 2D foils. Manual placement of preimpregnated plies on the carbon/epoxy mould.

B/ AFP manufacture at Avel Robotics for 2D foils.

C / Steel mould for IMOCA foils (2022). Steel sheet welded to a steel frame.

D / Manufacture of battens by AFP, which will be bonded together to produce a 3D foil.

(Photos Avel Robotics)

	

AVEL

Figure 16 : Diagram showing the principle of a 3D reinforced foil. Manufacturing steps: batten fabrication, bonding, machining, laminating outer layers.

A / Leading edge in carbon SM /epoxy (local reinforcement for impacts)

B and E / High density foam (to reduce weight)

C / Bar in carbon IM/epoxy made up of battens bonded together

D / Details of batten with around 80% unidirectional fibres, to resist bending (tension and compression). The plies at 45° resist the shear loads, those at 90° the transverse tension loads (reversed loading)

F / Trailing edge in carbon SM/epoxy (external plies bonded, local reinforcement

G / ±45° outer plies in HM carbon to absorb twist

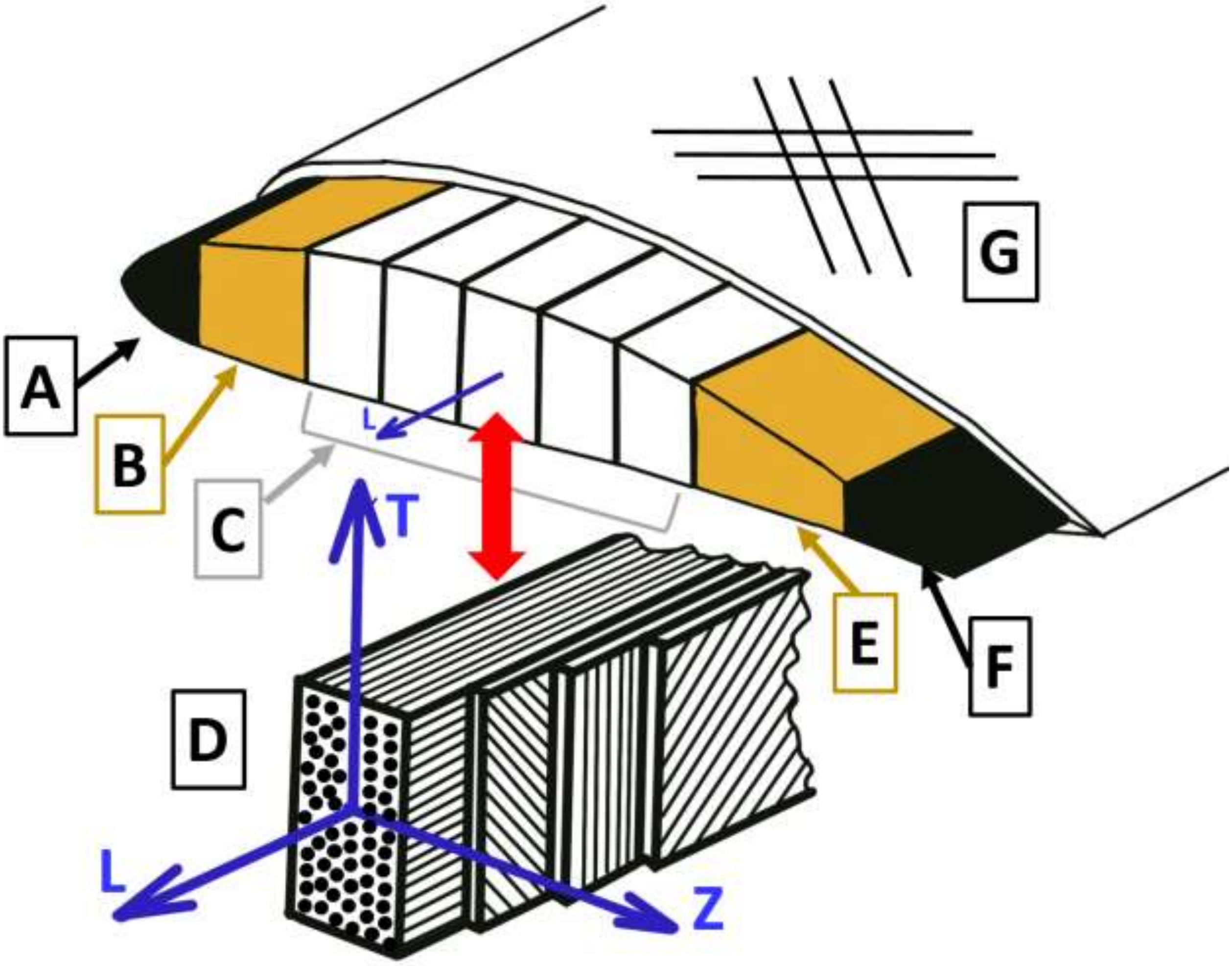

Figure 17: Mast SolidSail - 66m long, carbon fiber-reinforced composite material, approx. 15 tons mass (Photo Chantier de l'atlantique - France)

Fig 18 : Traditional sailcloth, woven polyester (DacronTM), surface and through-thickness section (268 gr/m²)

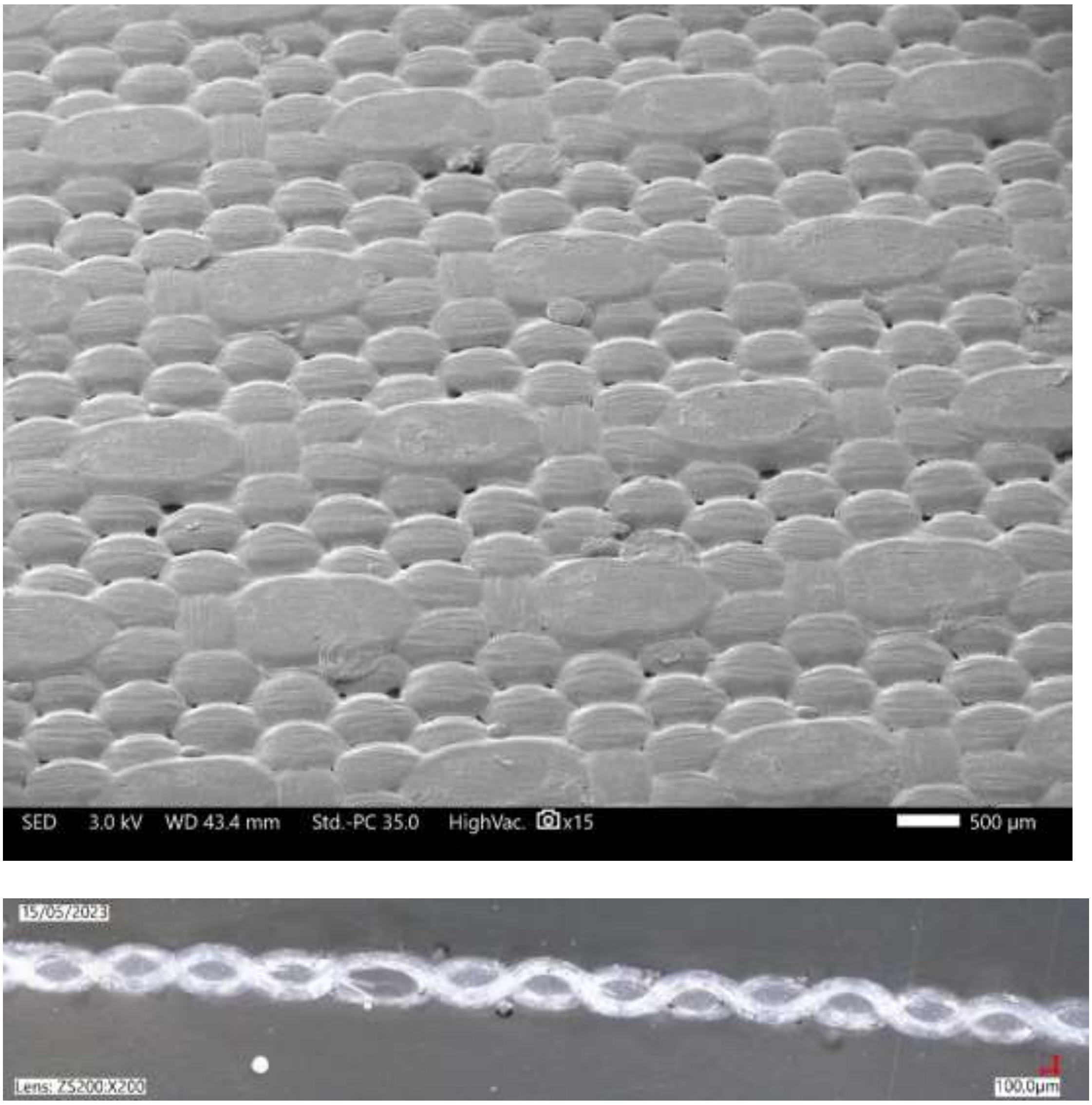

Figure 19 ; Laminated sail, impregnated stack of fibre plies (242 gr/m²), similar to TPT, surface and through-thickness section

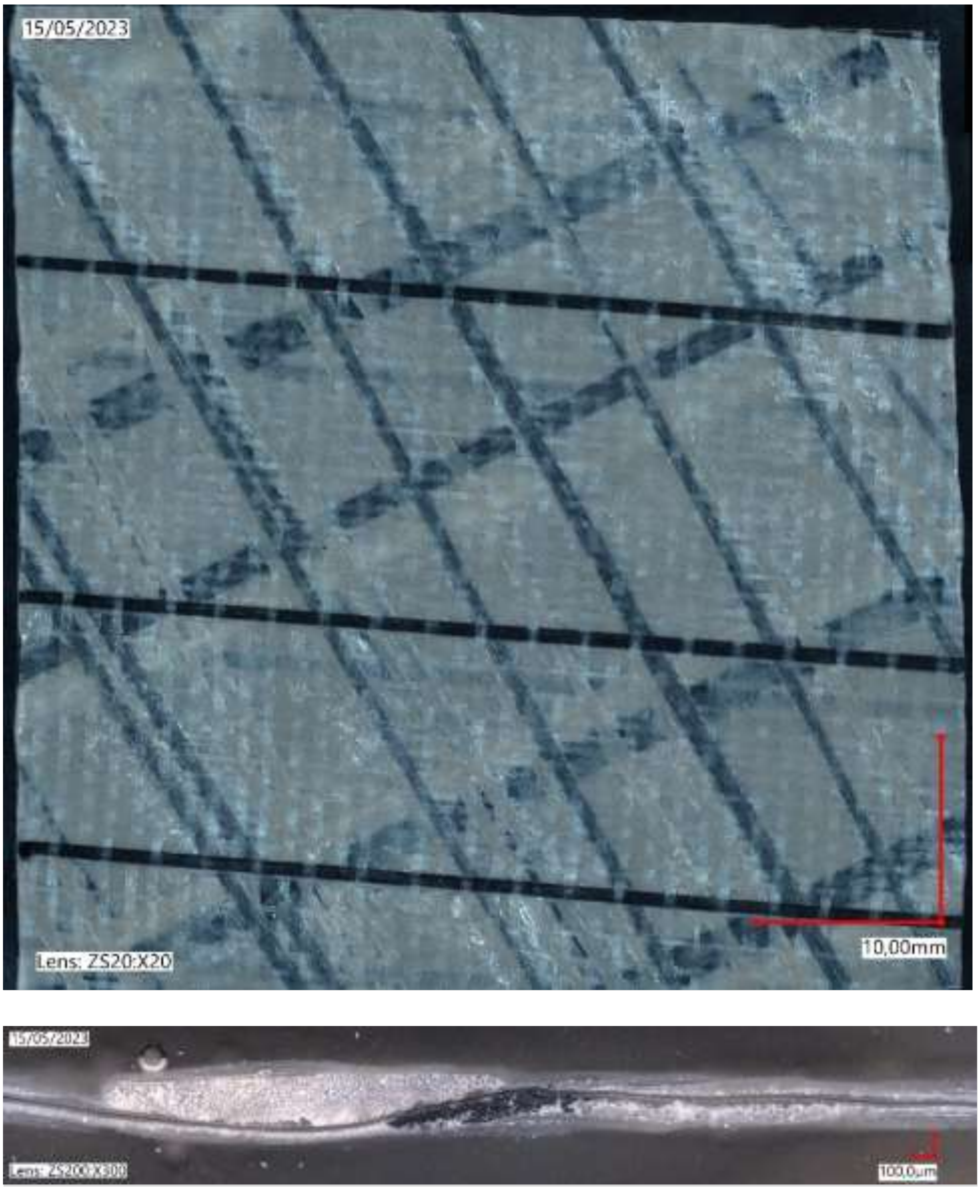

Figure 20 : Primary energy demand, and greenhouse gas (GHG) emissions to produce 1 kg carbon fiber (Adapted from [120]).

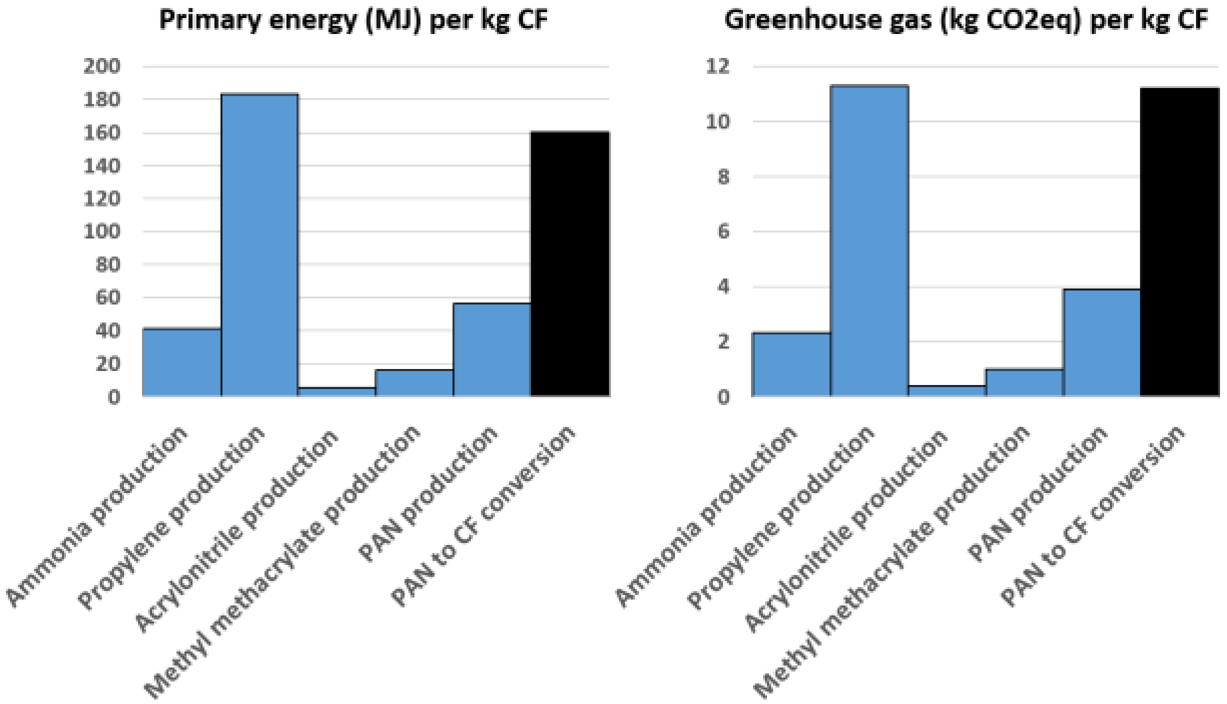

Figure 21: Main recycling methods for thermoset composite materials

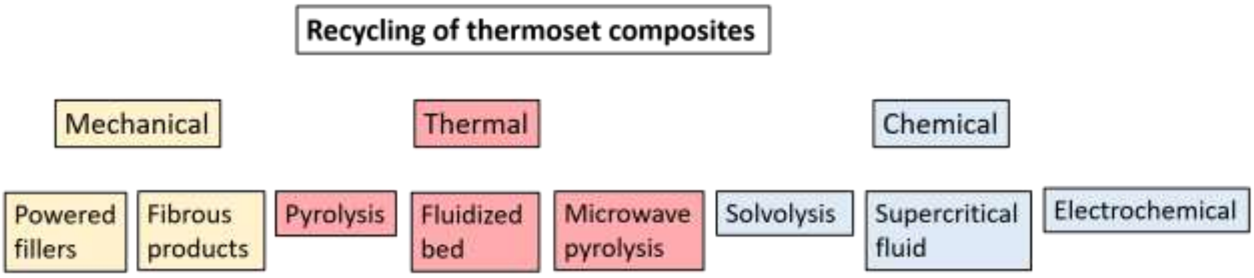

Figure 22. Tidal Turbine developed by Sabella, Quimper, France, with 5-meter long carbon/epoxy blades [188]

Figure 23: Catamaran We-Explore (length 18 m) with deck and mainsail reinforced by flax fibres

(Photo Explore, credit Martin Viezzer)

Figure 24. Different scales of polymer biodegradation in the environment

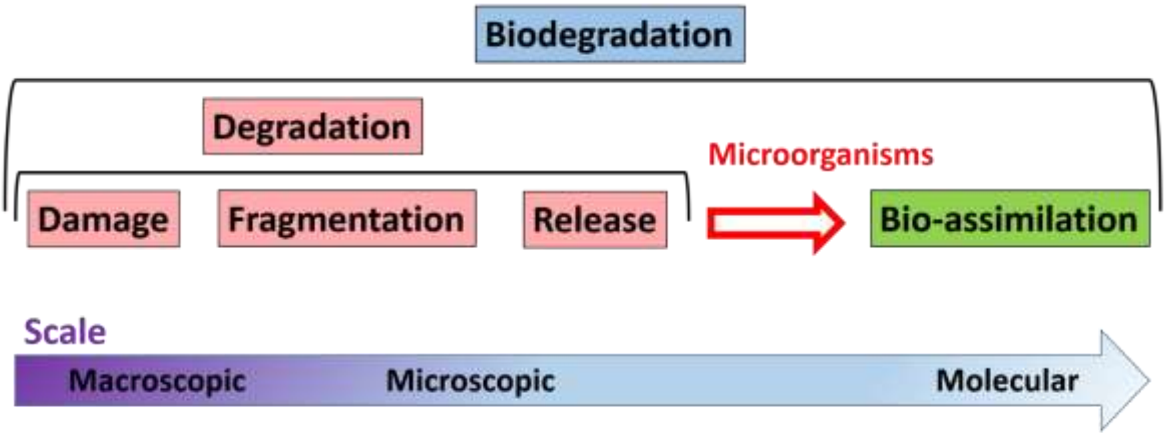

Figure 25 : Depicts how the concept of recyclability can be utilised for biocomposites

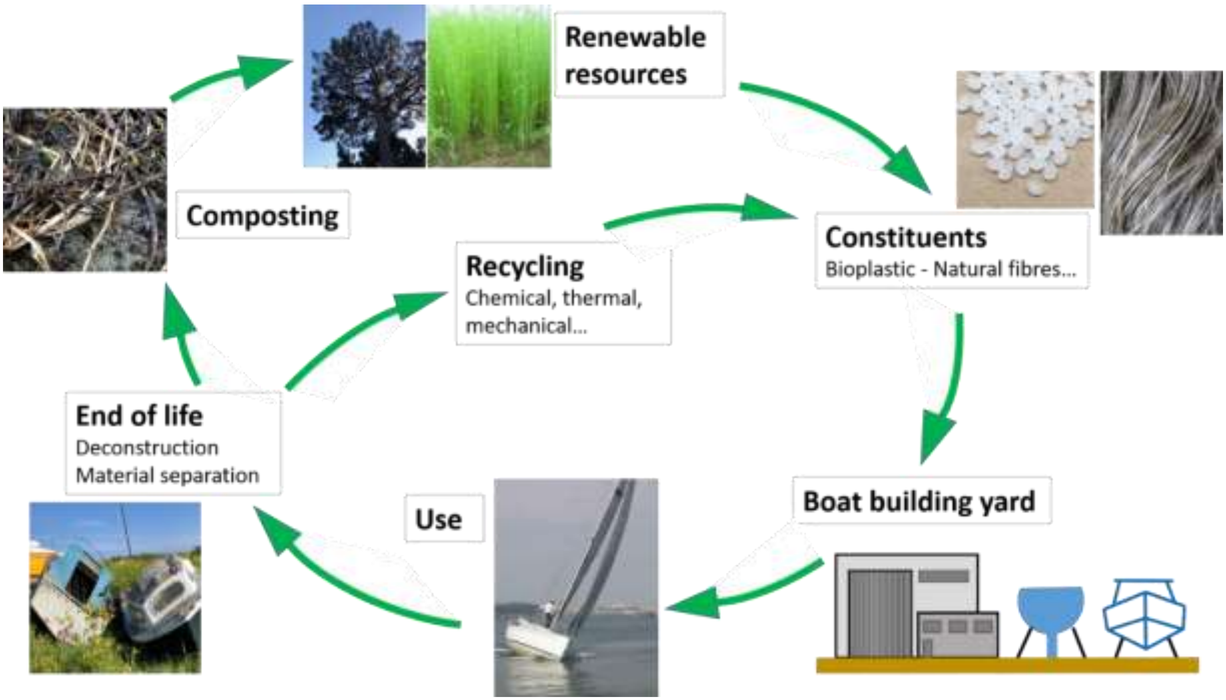

Figure 26: Design spiral for boats and ships (adapted from [244])

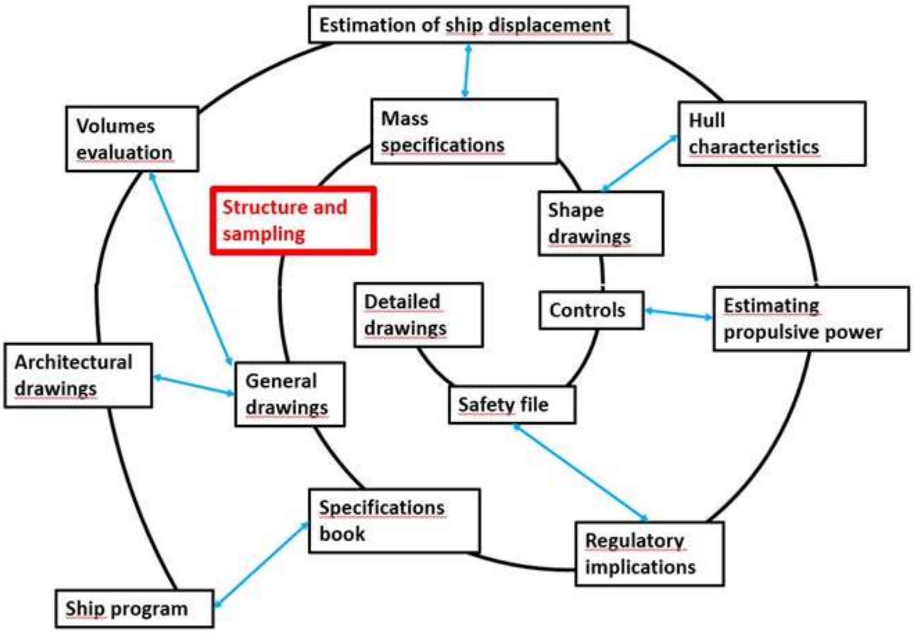

Figure 27 : Schematics of the design process for a sustainable boat structure in composite materials

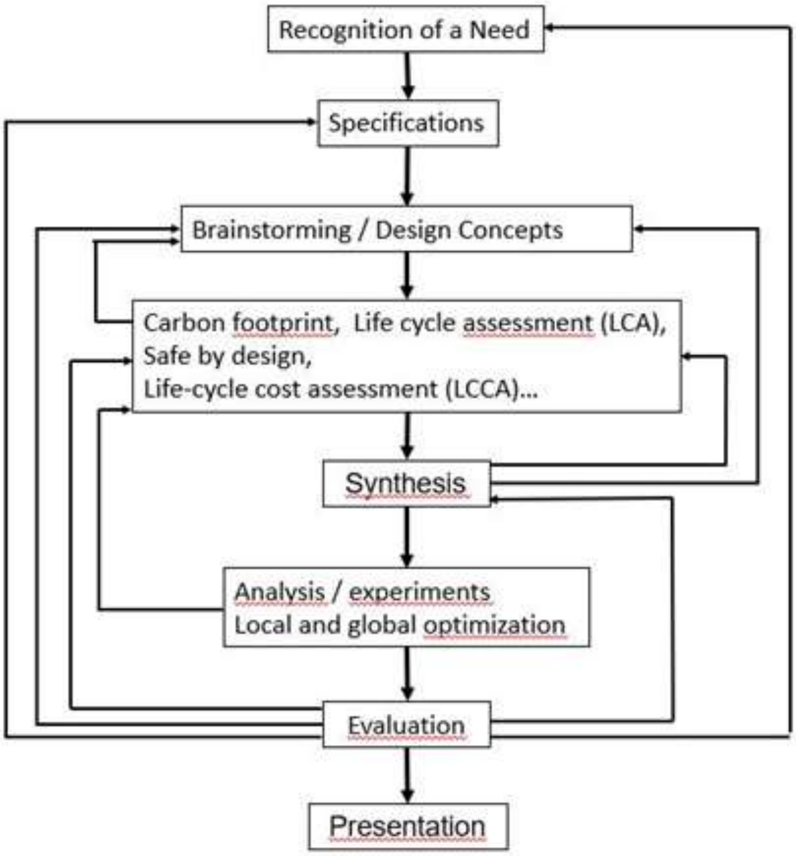

Figure 28 : a) Racing yacht designed and built in 2002 for the Americas Cup 2003 edition, 25 m long. The yacht has been stored since then, it weighs 3 tons of composite materials (hull and deck). b) Pleasure boat, 10m long, navigation since 1963 (Model: Pen ar bed built by Jouet boatyard in France). This boat has been in the water for 60 years, apart from maintenance and repairs, it is now on its 3rd motor.

a) b)

Figure 29 : Main areas which require sustainability studies