POLITECNICO
MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

Life Cycle Engineering of a yacht's structural composite component

Tesi di Laurea Magistrale in
Materials Engineering and Nanotechnology -
Ingegneria dei Materiali e delle Nanotcenologie

Author: **Federica Ravasio**

Student ID: 965621
Advisor: Prof. Roberto Frassine
Academic Year: 2021-22

Abstract

Yacht industry is one of the largest applications in terms of composite materials manufacturing and employment of structural composite components, due to their smart engineering properties: stiffness, lightness, durability, ease to manufacture. Traditionally, composite materials components constituting a recreational craft have a limited lifetime, identified as the use phase, and a much limited amount of the total is recycled or reused. These components heavily impact on the environment in terms of extraction of raw materials, processing, manufacturing, use and disposal.

The current project sets the basis for a wise, sustainable-driven design approach, by evaluating the environmental impact of the production of a composite component throughout its lifetime, by means of Life Cycle Assessments. The environmental analysis builds up in a more complex design approach: Life Cycle Engineering, which comprehends other aspects of product design, such as performance, durability, applicability; this concept of design could be scalable to the whole composite yacht industry.

The current work proposes an alternative in raw materials selection of a yacht's structural composite component on the basis of LCE, in order to reduce the environmental footprint of its production and prepare the path for a sapient sustainable design with composite materials.

Keywords: Life Cycle Engineering (LCE), Life Cycle Assessment (LCA), composite materials, sustainable design, yacht industry.

Abstract in lingua italiana

L'industria nautica è una delle maggiori applicazioni in termini di volumi di produzione di materiale composito e del loro impiego in componenti strutturali, grazie alle loro eccellenti proprietà ingegneristiche: rigidità, leggerezza, durabilità e facilità di produzione. Tradizionalmente, i componenti in materiale composito che costituiscono un'imbarcazione da diporto hanno una durata limitata, identificata come fase di utilizzo, e una piccola parte del composito che costituisce uno yacht viene riciclata o riutilizzata. Questi componenti hanno un forte impatto sull'ambiente in termini di estrazione delle materie prime, lavorazione, produzione, utilizzo e smaltimento.
Il progetto corrente pone le basi per un approccio progettuale accorto e sostenibile, valutando l'impatto ambientale della produzione di un componente in composito lungo tutto il suo ciclo di vita, attraverso la valutazione del Life Cycle Assessment (LCA). L'analisi ambientale si sviluppa in un approccio progettuale più complesso: Life Cycle Engineering (LCE), che comprende altri aspetti della progettazione del prodotto, come le prestazioni, la durata, l'applicabilità; questo concetto di progettazione potrebbe essere scalabile all'intera industria degli yacht in composito. Il presente lavoro propone un'alternativa nella selezione delle materie prime dei componenti strutturali in composito di uno yacht sulla base della LCE, al fine di ridurre l'impronta ambientale della sua produzione e preparare la strada per una progettazione sostenibile con i materiali compositi.

Parole chiave: Life Cycle Engineering (LCE), Life Cycle Assessment (LCA), materiali compositi, progettazione sostenibile, industria nautica.

Contents

1 | Introduction

The global attention to sustainability in all of its shapes has led every field to adapt to a constantly changing world and way of thinking: industrial environments more than any other sector need to question their approaches of product creation, since their production flow is directly proportional to the environmental impact onto our planet.

The traditional aims of a product engineer were bound to performance and durability goals, especially when related to high level engineering applications. This is the case of composite industry, mainly oriented on innovative engineering products in many sectors, among which stand out aeronautical, automotive, aerospace, energy and nautical fields.

Along with the present thesis I had the opportunity to explore a new workflow for the engineering design and fabrication of composite products in the nautical world. Particularly, I had the chance to cooperate with *Sanlorenzo S.p.A.*, leading shipyard in Europe with its Yacht Division, in order to set the bases for designing with a sustainability-oriented perspective.

The goal of the current thesis is to create and standardize a composites design methodology, being scalable and reproducible for composite materials manufacturing industry. This design approach will collect design variables and parameters also concerning environmental impacts, which will be evaluated with the aim to be central in the design definitions, in terms of raw materials choice, production process techniques and end-of-life treatments.

In order to do so, the present study analyzes a yacht's structural composite component as a whole: it assesses the environmental impacts related to its production, by means of a practice called Life Cycle Assessment. The latter represents the numerical parameter which assesses its environmental condition and could be used as a term of comparison to other design projects, by leaving unchanged technical and performance parameters.

The project concentrates on suggesting alternatives to the original design of a selected component, suitable for the generalization and scaling to other components, mainly for structural composite elements to be employed in marine environment. The use of new materials to be utilized will be evaluated, as well as new strategies of production. Also alternatives in terms of end-of-life treatments will be considered, such as recycling, reusing or remanufacturing: this would aim to keep the composite component in the circular economy loop as long as possible, thus reducing global raw material uptake and environmental impacts related to the disposal of the components at issue.

2 | Background

This chapter will define the fundamental aspects concerning composite materials, in order to understand the basis and the development of this master thesis work. In particular, a general overview of Glass Reinforced Polymers (GRP) and Carbon Fiber Composites (CFC) will be given first. Therefore their application will be discussed, with focus on marine environment, crucial for the aim of this research project. Finally, considerations about the environmental impact of composites, the research in progress and sustainable alternatives will be examined.

2.1. Composites materials: fiber reinforced polymers

The group of materials which can be defined as composite materials is extremely large. Its boundaries depend on definition. In general, a composite is considered as a combination of two or more materials, commonly referred to as constituents, and have material properties derived from the individual constituents. These properties may have the combined characteristics of the constituents or they are substantially different. Sometimes the material properties of a composite material may exceed those of the constituents. This general definition of composites includes natural materials like wood, traditional structural materials like concrete, as well as modern synthetic composites such as fibre or particle reinforced plastics which are now an important group of engineering materials where low weight in combination with high strength and stiffness are required in structural design.

In the more restrictive sense, a structural composite consists of an assembly of two materials of chemical-physical different nature. In general, one material is discontinuous and is called the reinforcement, the other material is continuous, mostly less stiff and weaker: it is called the matrix. The properties of a composite material depends on:

- The properties of the constituents,
- The geometry of the reinforcements, their distribution, orientation and concentration, usually measured by the volume fraction or fiber volume ratio,
- The nature and quality of the matrix-reinforcement interface.

In a less restricted sense, a structural composite can consist of two or more phases on the macroscopic level. The mechanical performance and properties of composite materials are superior to those of their components or constituent materials taken separately. The concentration of the reinforcement phase is a determining parameter of the properties of the new material, their distribution determines the homogeneity or the heterogeneity on the macroscopic scale. The most important aspect of composite materials in which the reinforcement are fibers is the anisotropy caused by the fiber orientation. It is necessary to give special attention to this fundamental characteristic of fibre reinforced composites and the possibility to influence the anisotropy by material design for a desired quality.

Summarizing the aspects defining a composite as a mixture of two or more distinct constituents or phases it must be considered that all constituents have to be present in reasonable proportions that the constituent phases have quite different properties from the properties of the composite material and that man-made composites are produced by combining the constituents by various means. Figure 2.1 demonstrates typical examples of composite materials.

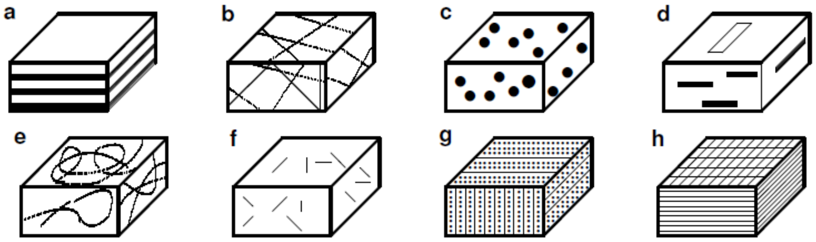


Figure 2.1: Examples of composite materials with different forms of constituents and distributions of the reinforcements. *a* Laminate with uni- or bidirectional layers, *b* irregular reinforcement with long fibres, *c* reinforcement with particles, *d* reinforcement with plate strapped particles, *e* random arrangement of continuous fibres, *f* irregular reinforcement with short fibres, *g* spatial reinforcement, *h* reinforcement with surface tissues as mats, woven fabrics, etc. [1]

Composites can be classified by their form and the distribution of their constituents. The reinforcement constituent can be described as fibrous or particulate. The fibres are continuous (long fibres) or discontinuous (short fibres). Long fibres are arranged usually in uni or bidirectional, but also irregular reinforcements by long fibres are possible. The arrangement and the orientation of long or short fibres determines the mechanical properties of composites and the behavior ranges between a general anisotropy to a quasi-isotropy.

Composite materials can also be classified by the nature of their constituents. According to the nature of the matrix material we classify organic, mineral or metallic matrix composites.

The most advanced composites are polymer matrix composites. They are characterized by relatively low costs, simple manufacturing and high strength. Their main drawbacks are the low working temperature, high coefficients of thermal and moisture expansion and, in certain directions, low elastic properties. Most widely used manufacturing composites are thermosetting resins as unsaturated polyester resins or epoxy resins. [1]

Among those, particular interest is associated to Glass fiber-reinforced polymers (GFRP) and Carbon fiber-reinforced polymers (CFRP). Their main characteristic and peculiarities will be investigated in the following sections.

2.1.1. Glass fiber-reinforced polymers

Glass fiber-reinforced polymers are widely employed in various applications, due to their low cost, strength, flexibility, stiffness and resistance to chemical harm. The versatility of glass fibers rely on the many ways in which they could be arranged: roving's, chopped strand, yarns, fabrics and mats. Each type of glass fibers have unique properties and are used in different applications in the form of polymer composites.

Glass fibers are peculiar because of their limited cost and high resistance. The main drawbacks in their usage are related to their low modulus and moderate abrasion resistance. They are characterized by a quite high density and by a difficult adhesion to matrices, especially in humid environments, since they have hydrophilic surface.

There are several types of glass fibres, which are distinguished in chemical composition, resulting in different physical and mechanical properties. Among the variety of glass fibers, the most common kinds are E-glass and S-glass, respectively high strength plus electrical resistivity reinforcement and high strength, modulus and stability of the fibres. Their properties are summarized in Table 2.1:

Fiber	**Density** (g/cm^3)	**Tensile strength** (GPa)	**Young's modulus** (GPa)	**Elongation** (%)	**Poisson's ratio**
E-glass	2.58	3.45	72.3	4.8	0.2
S-glass	2.46	4.89	86.9	5.7	0.22

Table 2.1: Physical and mechanical properties of glass fibers. [2]

The process of continuous fibers production consists in an high-temperature conversion of borosilicates and aluminum oxides into a homogeneous melt. The latter is then subjected to fiberization by extrusion: the molten glass passes through a bushing made of an erosion-resistant platinum/rhodium alloy with very fine orifices. In the extrusion process the melt temperature decreases, the fibers are treated with lubricants and coupling agents (sizing); finally, the filaments are collected in strands and wound in coils. The produced fibers are assembled in rovings, cut in order to form mats or textiled to produce fabrics, which will be employed by composite manufacturers. [3]

2.1.2. Carbon fiber-reinforced polymers

Another important composite material is the class of Carbon fiber-reinforced polymers, used throughout industry for their excellent mechanical properties; in particular, these composites show high specific stiffnesses and specific strengths.

Carbon fibers generally have excellent tensile properties, low densities, high thermal and chemical stabilities in the absence of oxidizing agents, good thermal and electrical conductivities, and excellent creep resistance. They have been extensively used in composites in the form of woven textiles, prepregs, continuous fibers/rovings, and chopped fibers.

The composite parts can be produced through filament winding, tape winding, pultrusion, compression molding, vacuum bagging, liquid molding, and injection molding.

There are different kinds of carbon fibers, they are distinguished by their carbon content: the main division is between graphite fibers, which present a carbon content greater than 99%, and carbon fibres, with a carbon content between 80% and 95%. Physical and mechanical properties are strongly influenced by the chemical composition of carbon fibers.

The main characteristics of carbon fibres, divided for high strength fibers and high modulus ones, are collected in Table 2.2.

Fiber	**Density** (g/cm^3)	**Tensile strength** (GPa)	**Young's modulus** (GPa)	**Elongation** (%)	**Poisson's ratio**
Carbon (high-strength)	1.5	5.7	280	2.0	0.28
Carbon (high-modulus)	1.5	1.9	530	0.36	0.27

Table 2.2: Physical and mechanical properties of carbon fibers.

The production process of carbon fibers starts from polyacrylonitrile (PAN) and rayon filaments; they are subjected to a first treatment, called stabilization, at 200-250°C in air and loaded in tension, in order to orient their molecular structure in the load direction, which will favour the development of the extremely oriented graphitic structure. Fibers are then treated at 1500°C in inert atmosphere, this phase is called carbonization: it aims to eliminate most elements constituting the precursor, other than carbon. The ultimate step for the production of carbon fibres is called graphitization, performed at 3000°C in inert atmosphere. At this stage the crystalline structure can be fully developed and the outstanding mechanical properties reached. [4]

2.2. Fiber reinforced polymers in marine environment

Structures to be used in marine environment need to sustain high stresses deriving from the action of wind, waves and tides. Moreover, they have to endure severe working environments, such as splash zones and seawater submerged parts.

All the conditions mentioned above led to the development of large studies in the past decades, concentrated on finding the most suitable materials to fulfil these design constraints. Composite materials, more specifically fiber-reinforced polymers, presented the best matches in characteristics to be applied in those severe working environments, while guaranteeing the demanding mechanical performances.

Concerning the shipbuilding sector, FRPs have been extensively incorporated in the production of main structures, including hulls, decks and many other fundamental components. Composite technology has allowed manufacturers to improve the quality of products obtaining stiff and light structures, with benefits in terms of sailing performances and working life.

Stiffer hulls and decks are the main applications where the shipbuilding industry has adopted composite sandwich structures, composed by two skins with high stiffness and strength placed on the external faces of a component and by a soft and thick core. Stiff skins provide high bending stiffness, meanwhile, the core supports the shear and compressive stresses and stabilizes the skins preventing global and local instabilities. The weight reduction results in larger cargo capacity, fuel-saving, lower inertia, and increased ship stability and buoyancy. In addition, FRPs show satisfactory corrosion resistance in the marine environment and require less maintenance. [5]

The design process with composite materials is challenging due to the high number of parameters involved. The goal of a design project is to find the best combination between reinforcing materials, matrices and core materials, taking into account the arrangement of the plies and the properties of the resulting composite laminates.

For what it concerns fiber reinforcements, glass fibres are the most commonly used in large composite structures; E-glass fibers are the prevailing kind of reinforcement employed in marine applications, due to their good maximum tensile strength, ultimate tensile strain combined with outstanding resistance to moisture and chemical aggression, combined with excellent electrical insulation properties.
Carbon fibers represent a valid alternative to glass fibers, with higher strength, stiffness and cost. Nevertheless, carbon fiber composite structures are more convenient from a design point of view and can be also cost-effcient considering the overall cost (raw material and manufacturing cost). Indeed, the amount of reinforcement can be reduced so that the higher price of carbon fiber can be balanced, without decreasing the performance of the structure.

The matrix is the composite constituent responsible for many important functions, for instance holding the reinforcement phase in place, deforming and distributing stress to the reinforcement under applied loads or stress, binding the fibres together and transferring load to the fibres and providing rigidity and shape to the structure, isolating the fibres so that individual fibres can act separately and stopping or slowing the propagation of cracks, and providing protection to the reinforced fibres against chemical attack and mechanical damage. [6]
Most common polymeric matrices employed in industrial marine applications are of thermosetting type, such as Unsaturated polyester resins, Vinyl ester and Epoxies.

The advantages of UP resin are its dimensional stability and affordable cost. It is capable of producing very strong bonds with other materials, with good toughness and crack resistance capability. Moreover it is easy to handle, process, fabricate and has good balance of mechanical, electrical and chemical properties. Some special formulations offer high corrosion resistance and fire retardant. [7]
Most marine application components are made of vinyl ester resins: this thermosetting polymer requires a catalyst and an accelerator for curing at room temperature. They withstand chemical corrosion and exhibit an acceptable behaviour with respect to absorption and hydrolytic attack. However VE resins exhibit high shrinkage (7–10%), and high levels of styrene emission that require dedicated systems to minimize worker expo-

sure. They show mechanical properties and prices which are positioned halfway between polyester and epoxy resins.

Epoxies, indeed, provide significant improvements in the quality and performance of the boat and eliminate dangerous emissions, they also have lower viscosities and can be cured at low temperatures, being particularly suitable for infusion processes. Epoxies have higher elongation, tensile strength, and modulus than PE and VE. Therefore, designers can increase fiber content - due to the better impregnation assured by epoxy resins - and decrease the number of layers of the laminates without compromising the mechanical behavior of the composite parts produced. The achieved weight reduction guarantees higher speed and reduces fuel consumption. Furthermore, due to the reduced cure shrinkage (less than 2%), smooth and continuous surfaces can be achieved directly on the mold.

Table 2.3 collects the main mechanical characteristics of the aforementioned matrices.

Fiber	**Density** (g/cm^3)	**Tensile strength** (MPa)	**Tensile modulus** (GPa)
Unsaturated polyester	1.2 - 1.5	40 - 90	2.0 - 4.5
Vinyl ester	1.2 - 1.4	69 - 83	3.1 - 3.8
Epoxy	1.2 - 1.4	35 - 100	3.0 - 6.0

Table 2.3: Physical and mechanical properties of common thermosetting resins. [8]

In marine sandwich structures, polymeric foams (polystyrene (PS), polyvinyl chloride (PVC), polyurethane (PU)) and honeycomb are mainly used as core material.

Composites sandwich structures are created by inserting a lightweight core between the two face sheets, this leads to improve bending stiffness and strength compared to a single layer homogenous structure, with the addition of limited weight. The viscoelastic core has aalso a high inherent damping capacity: when the composite plate undergoes flexural vibration, the damped core is constrained to shear. This shearing causes the flexural motion to be damped and the vibrational energy to be dissipated. [9]

Advanced composite materials have encountered a reduced use to manufacture larger commercial vessels due to their high initial costs and stringent performance requirements. However, the development of new materials and novel manufacturing processes are constantly diminishing the impact of these obstacles promoting wider use of composites in this sector. [5]

2.3. Sanlorenzo Yacht Division

Sanlorenzo is an italian shipbuilding company which is leader in composite products within yacht industry. Sanlorenzo Yacht Division produces an average of 75 unit per year: Sanlorenzo's recreational crafts have length between 76 and 132 ft (23 and 40 m), they are mainly built with glass fiber and carbon fiber reinforced polymers, by both hand lamination and resin infusion.

Every year approximately two lines are launched and add up to the entire Sanlorenzo's product range. Their engineering design is evolving every year and becoming more innovative with every project.
Sanlorenzo is constantly working towards innovative design approaches, which must include a sustainability-vision, especially when working with composite materials.

2.4. Environmental impact of composites

As mentioned in Section 2.1, composite materials are distinguished from traditional structural materials for their extraordinary combination of stiffness, strength and lightness, which allows to reduce the total mass of the components, in favour of transportation service and handling, assembly, installation and operation energy request. All of these benefits, together with the superior durability of the material in common operating conditions, allow to state that the use of composites is environmentally favourable: lower energy usage and lower greenhouse gas emissions, higher durability of the products, even in absence of maintenance, better performances and safety.

When a composite component completes the usage phase, it is essential to foresee its disposal treatment. "Circular economy" is a popular concept nowadays, that rules economic strategies: it modifies the traditional "linear economy", that is based on the typical scheme extract/produce/use/disposal, by closing the loop; production and consumption model is radically modified: it encloses sharing, loans, restoration, reconditioning, reuse and recycle of materials and products existing, in order to keep them in the loop as long as possible.
Composite materials fit well in the circular economy scheme: for what it concerns environmental impacts, raw materials production processes have a prevalent effects in terms

of energy consumption and greenhouse gases. A better employment of raw materials may contribute to both limiting those factors and providing continuity to the supply chain of raw materials.

In order to achieve this goal, a hierarchy in end-of-life treatments has been introduced, which promotes strategies of product fixing and reusing, in order to extend their service life and keep them in the use phase. From this point of view, composite materials are extremely suitable, since they are durable, resistant to damage and environmental attack, plus easy to fix.

In conclusion, it can be stated that composite materials are ideal for circular economy, since service life of a composite component is generally a relatively low fraction of the complete lifetime of their constituent materials. Composite materials lend themselves well to be restored and reused in other structural applications.

2.4.1. Composite materials recycling

Whereas reuse is not an option, further alternatives are recycling, recover or final disposal.
Recycling refers to the practice of treating a component at its end-of-life or production scraps in order to create a new product or a material with a different functional use.
Recover means to convert waste into fuel or thermal energy, after removing every component which can be reused.
Waste disposal or incineration without energy recovery are the least preferable treatment, since they do not allow any material or energy recovery.

In theory, with composite materials it could be possible to reacquire the original precursors without loss in performance, from a circular economy point of view. This approach could allow for a closed loop of the component's life cycle, resulting in the production of a new product for the same purpose, without the introduction of new raw materials; thus leaving unchanged the balance between demand and supply.
In a broader sense, complete circularity is reachable with composite materials, but at the moment, economic feasibility and environmental impact of the recovery processes must be verified/considered.

Nowadays, the main technology used for composites recycling is through kilns for cement production (also known as co-processing), in which waste is split into both cement composition and fuel for the process, while contributing to the reduction of CO_2 emissions.

Composite materials can also be recycled by mechanical and electromechanical recycling (high-voltage pulse fragmentation), by thermal processes of recycling (pyrolysis, fluidized-bed and depolymerization) or thermochemical ones (solvolysis).

In the following chapters, the environmental impacts associated to the production of composite materials components will be investigated and discussed. The current work focuses on the production of Sanlorenzo S.p.A., the company I had the pleasure to meet in my recent internship and which gave me the opportunity to explore the world of composite materials in yacht-building sector.

2.5. Sustainable alternatives to traditional composites

The picture discussed herein before focused on the existing methodologies and technologies in use, taking into account the recycling options suitable for the current composite components situation. However, the growing general interest to environmental issues and climate change makes it urgent to renew the concept of designing with composite materials, with a new circular and sustainable outlook.
The latter reduces into the necessity to operate with two main approaches:

- design with new raw materials, chosen because of their recycling, re-usability potential or because of their limited environmental impact in their production phase, in order to reduce the overall materials supply and guarantee the similar performances after a number of application cycles;
- design parts and their assembly considering the need of later separation of the materials constituting the component, in order to treat them separately at their end of life.

A feasible path to take is the one of considering Bio-Composites (BCs) as raw materials alternative to traditional Fiber Reinforced Polymers (FRPs). The benefits of adopting BCs over FRP composites are evident within the academic literature. They are produced from naturally-renewable and abundant precursor feedstocks, and possess properties equivalent, on a weight basis, to their synthetic counterparts.

2.5.1. Sustainable composite materials for marine environment

In order to address the wide world of sustainable design, first it is common practice to enlist the design requirements and the system in which the new composite components will operate.
Marine structures are exposed to relevant environmental challenges: therefore materials with elevated resistance are preferred, in order to sustain high loads generated from wind, waves and tides. Moreover, being lightweight and corrosion resistant are two main aspects to ensure comfort in use and durability of every boat, watercraft or vessel employed in marine environment. [5]

Therefore, new raw materials combinations of composite materials constituents will have to take into account the mentioned limitations, in order to match marine environment requirements, other than specific mechanical constraints which will be discussed in the following chapters of the current study.

The main constituents that will be object of research are: fibers, matrices and core materials. The main literature and market alternatives will be now outlined.

Fibers

A first category of fibers whose interest is growing in marine applications are natural fibers.
Natural fibers including those extracted from sisal, jute, coir, flax, hemp, pineapple, and banana have been used more and more in the past two decades to create new environmentally friendly and biodegradable composite materials. Recent studies in natural fiber composites offer significant improvement in materials from renewable sources with enhanced support for global sustainability. These natural fiber composites possess high/moderate strength, thermal stability when they are recyclable, but the problems of using pure biodegradable polymers are their low strength and transition temperature. [10]

Plant fibers

Flax fibers - Flax fibers are potentially outstanding reinforcing fillers in thermoplastic biocomposites. These biocomposites could have a great potential in lowering the usage of petroleumbased plastics. Automotive, building and appliance industries are increasing the utilization of flax fibers day by day due to cost saving, nonabrasiveness and the green movement. Biocomposites containing thermoplastics and modified flax fiber have mechanical properties comparable with those of glass fiber-based thermoplastic (LLDPE/ HDPE) composites. Boset al. have investigated the mechanical properties of fl ax/polypropylene composites, manufactured both with batch kneading and an extrusion process, and compared with the properties of natural fiber mat thermoplastic composites. [11]

wood core and skin make up most of the flax (*Linum usitatissimum*) stem. Technical fibers are made up of 10–40 elementary fibers that range in thickness from 0.1 mm to 0.8 mm and are 20 mm to 50 mm long. The fiber in a single flax strand has many layers. There is a thin main wall in these layers containing cellulose and hemicellulose. The secondary wall strengthens the fiber while also allowing microfibrils to form. These microfibrils are made up of 30%–100% cellulose. Microfibrils with more cellulose have a higher tensile strength. Because of the lumen's hollow core and the cellulose microfibrils' orientation, flax fiber has unique characteristics. [10]

Jute fibers - Jute take nearly 3 months, to grow to a height of 12–15 ft, during season and then cut and bundled and kept immersed in water for "Retting" process, where the inner stem and outer, gets separated and the outer plant gets 'individualized', to form a Fiber. Then the plant get separated and washed to remove dust from the plant. The fiber after drying is taken to Jute mills, for getting converted to Jute yarn and Hessian. [10]

Sisal fibers - Sisal fibers are extracted from the leaves of sisal plant. The fibers are extracted through hand extraction machine composed of either serrated or non serrated knives. The peel is clamped between the wood plank and knife and hand-pulled through, removing the resinous material. The extracted fibers are sun-dried which whitens the fiber. Once dried, the fibers are ready for knotting. A bunch of fibers are mounted or clamped on a stick to facilitate segregation. Each fiber is separated according to fiber sizes and grouped accordingly. To knot the fiber, each fiber is separated and knotted to the end of another fiber manually. The separation and knotting is repeated until bunches of unknotted fibers are finished to form a long continuous strand. This Sisal fiber can be used for making variety of products. [10]

Mineral fibers

Basalt fibers - The majority of the world's countries contain the common volcanic rock known as basalt, which is perfectly suited for the production of fibers. Its chemical structure is nearly related to glass. The most important components of basalt are SiO_2, Al_2O_3, CaO, MgO, Fe_2O_3 and FeO. Since the various oxides combine to form a large, crosslinked molecule with primary bonds, basalt and glass can be thought of as a particular class of polymer. Between 1350 and 1700 °C, basalt rocks are molten. Basalt solidifies into a glassy amorphous phase when it cools quickly. Slower cooling results in a partially crystalline structure, an assembly of minerals. Basalt fibers are good electric insulators, biologically inactive and environmentally friendly. [12]

For what it concerns mechanical properties, Table 2.4 summarize the main mechanical properties of the aforementioned fibers. Glass fibers and Carbon fibers properties are also reported, in order to facilitate comparisons between new raw materials and traditional ones.

Fiber	**Density** (g/cm^3)	**Tensile strength** (GPa)	**Young's modulus** (GPa)	**Elongation** (%)
Flax	1.5	0.345 - 1.035	27.6	2.7 - 3.2
Jute	1.3	0.393 - 0.773	26.5	1.5 - 1.8
Sisal	1.5	0.511 - 0.635	9.4 - 22	
Basalt	2.7	1.43 - 4.9	71 - 110	3.1 - 3.3
E-glass	2.58	3.445	72.3	4.8
S-glass	2.46	4.890	86.9	5.7
Carbon (high-strength)	1.5	5.7	280	2.0
Carbon (high-modulus)	1.5	1.9	530	0.36

Table 2.4: Physical and mechanical properties of fibers.

The performance of natural fibre composites can be optimised when fibres receive a chemical treatment, for instance, alkali (mercerisation), acetylation, and anhydride treatments, or physical treatments, such as plasma or corona treatments, as well as increasing fibre/matrix adhesion by polymer modification. [13]

Resins

Traditional thermosetting polymers have largely been employed in composite production, due to their characteristics [5]:

- strength-to-weight ratio for lighter-weight durability,
- dimensional stability for lasting performance,
- corrosion resistance for deterioration-free operations,
- design flexibility for use in complex shapes.

However, at components' End of Life thermosetting polymers cannot be reused to produce new parts, since their intermolecular bonds (cross-links) are not reversible, therefore the only way for disposal of those products is by incineration - or some recycling treatments that aim to save the fiber of the composite material in order to reuse them in other contexts.

Thermoplastic polymers

An alternative to thermosetting resins are thermoplastic polymers to act as matrices for composite production. The reasons behind the choice of thermoplastic resins over thermosetting are multiple: they present higher toughness, they usually have higher transition temperatures (Glass transition temperature and Melting temperature) than thermosets. Thermoplastic resins are thermoformable for an ideally infinite number of times, therefore allowing theoretically for materials recycling. The main disadvantage of this class of polymers is the high viscosity, that hinders optimal fiber impregnation, preventing the stresses continuity, ensured by an efficient impregnation of the fibers in a composite.

Application fields of thermoplastic matrices are differentiated between short-fibers composites, for which injection moulding is the main technology for components production, and continuous-fibres composites, mainly employed for structural purposes. The latter are reserved for high temperatures applications, they allow to obtain high performances products, able to operate in continuous use at temperature above 300°C.

Another limitation of the use of thermoplastics as composite matrices is the elevated processing temperatures, that require specific equipment and higher costs with respect to thermosets. In order to overcome this drawback, it has been synthesized a particular thermoplastic resin that is activated and can be infused with the same processing techniques used by thermosetting resins: ELIUM 150.

The ELIUM 150 is a low viscosity liquid, thermoplastic resin for infusion and RTM processes., through the use of the same low pressure processes and equipment used today to produce thermoset composite parts, these formulations lead to the production of thermoplastic composites reinforced by continuous glass, carbon or natural fibers. The resulting thermoplastic composite parts show mechanical properties similar to those of parts made of epoxy resins while presenting the major advantages of being post-thermoformable and recyclable and of offering new possibilities for composite/composite or composite/metal assemblies.

A limitation of the current study is the difficulty to address a topic such as sustainability, which is wide and complex, due to the high number of parameters which influence the analysis.
A simplified version of an LCA study is to compare the impacts related to the production of a composite component with different raw materials. Thus the effects on the environment rellated to the production of raw materials would be compared and analyzed. This way to proceed is allowed by the fact that all the other parameters in a composite component production remain unchanged: functional unit, system boundary and processing are the main unchanged parameter, unless different raw materials require specific production needs.
The latter is the strategy with which this study will be conducted, by considering the only design option of raw materials alternatives.

However, in order to perform a complete and quantitative impact analysis on the feasible alternatives to the production of traditional composite materials, it should be considered the whole lifecycle loop of the components. With a view to include recycling or reuse as alternative ways to treat a composite end of life, the latter would be needed to be included in the LCA study: many are the combinations with which matrix, fibers and other constituents would interact in different treatments. Many are also the scopes of recycling, in the wide world of composite recycling, with different treatments, fibers, matrices, energy could be recovered. Also other resources could be collected, such as hydrocarbon products, matrix rich or fiber rich powder to be employed as filler in other production processes.

2.6. End of use: Design for X

Designing with end of life (or end of use, for the products here treated) scenarios in mind has become particularly prevalent. To prevent the loss of material from a technical product system at the end of its service life, the European Waste Hierarchy regulates the order of preferential waste treatment. End of use treatment should be considered during the design phase, with the aspiration to repurpose and reuse the component, preventing the least-desirable waste treatment options, such as landfill and incineration. Disposal at end of use can have a significant effect on environmental impact.

Design for X (DfX) is a design ethos, whereby X can have multiple definitions, ranging from Recycling to Serviceability. Within the available definitions, there are three which cover end of life processes, in order of descending desirability:

- **Design for Reuse (DfRu)** — Using and re-using a component for its originally intended application for as long as safely possible through repairs and maintenance checks.
- **Design for Repurpose (DeRp)** - Repurposing a structure for a secondary role, with the least amount of processing and transportation possible to minimise the environmental impact.
- **Design for Recycle (DfRc)** - Traditionally, DfRc involves an active consideration of how materials will be compatible with recycling processes, such as grinding or pyrolysis.

In the following sections it will be analyzed the environmental impact of a part of the Production of Sanlorenzo Yacht Division and proposed solutions to reduce the environmental footprint of the composite creation process.

3 | Environmental Impact Analysis on SD90/s T-Top

The current analysis focuses on the evaluation of the environmental burdens associated to the production of a selected portion of a motor yacht building process. The latter comprehends a complex and elaborate list of operations, to be competed in a time span of about one year.

The area of interest of the present work is chosen to be concerning the first processing division of a yacht building process: the heart of the research will be set in the composite structures making of the motor yacht at issue. The intent is to set the focus on the most important chapters of a boat creation, the crucial composite forming and material selection, which allow for high performances, lightness and durability of the finished product.

The product selected for the investigation of the production steps is SD90/s, a new motor yacht with the exclusive exterior design by Zuccon International Project and interior design by Patricia Urquiola, for Sanlorenzo Yacht Division.

The prototype was launched in 2022 and immediately stole the market attention thanks to its elegant layout and perfect dimensions.

Figure 3.1: SD90/s.

The workflow of the production of a recreational craft, such as SD90/s, consists in multiple steps, which result in two main phases: structural composite production, which consists in the whole composite moulding and assembly and the fitting step, which comprehends painting cycles, interiors furnishing and completion of the craft.

The main transformation technology employed to build the complex composite parts of a Sanlorenzo yacht hull is hand lamination: the selected textiles and cores are placed on a mould, with the correct lamination sequence, wet by the resin, by means of spray nozzles or paint rollers. The goal of complex geometries is fulfilled only by means of an elaborate layout of parts, which originate from a carefully studied composition of moulds, assembled together with precise decompositions, in order to guarantee proper extraction of the moulded parts.
For what it concerns the production of decks and deckhouses, the preferred technique is resin infusion, due to the limited complexity of the moulds and to their mainly planar extensions.

3.1. Product description

The product chosen for the current study is SD90/s. Its design focus was set onto sustainability of the exterior and interior furnishing, created by Patricia Urquiola.

Figure 3.2: SD90/s - Interior design, Main Deck.

Figure 3.3: SD90/s - Interior design, Vip Cabin.

Since the project's aims looked towards a sustainable design, I decided to pursue this path also working on composite materials structural components, as outlined in the following sections.

Figure 3.4: SD90/s - Exterior design.

3.2. Spare pieces outline

For each yacht model of Sanlorenzo yachts, the macro parts are identified as hull, deck and deckhouse. Every macro piece comes from a main mould with the least number of decompositions possible, in order to ensure the easiest removal of the part from the mould.

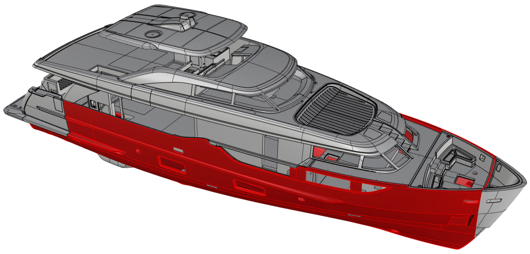


Figure 3.5: Representation of SD90/s hull.

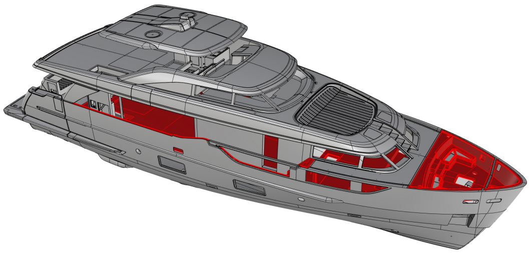


Figure 3.6: Representation of SD90/s deck.

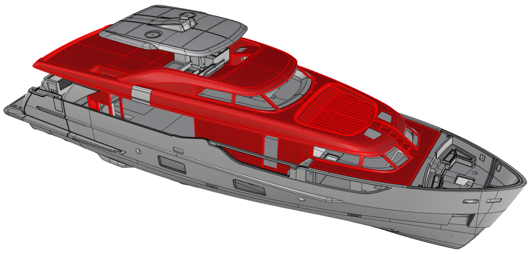


Figure 3.7: Representation of SD90/s deckhouse.

However, the simple division of the macro pieces is not sufficient to fulfil the design ge-

ometries, therefore spare pieces are introduced in the boat building process. They consist in parts of reduced dimensions with respect to the macro parts, which are moulded separately and assembled on the yacht structure at a later stage of the production.
While the macro parts that have structural purposes have composite joints which aim to the rigid bonding among them, most spare pieces are bonded to their respective macro piece with structural adhesives.
Spare pieces operate as auxiliary structures, generally they do not contribute to the structural stability of the yacht itself, they need to sustain lower loads with respect to the macro parts.

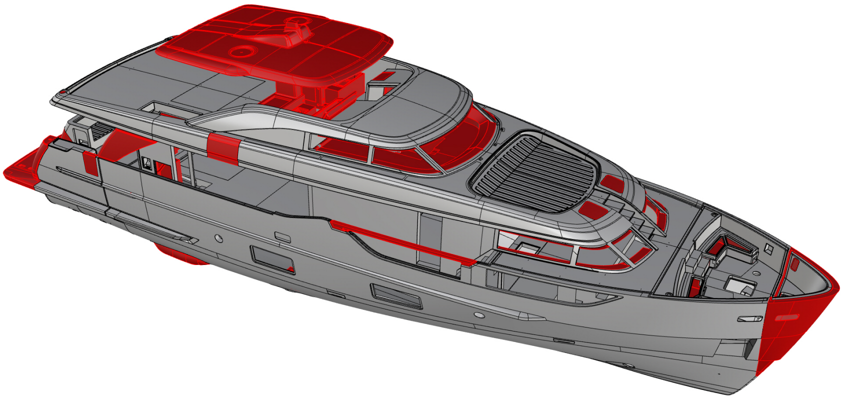


Figure 3.8: Focus on SD90/s spare pieces.

All the mentioned characteristics of spare pieces are relevant for the current study as a matter of environmental impact and justify the present work focus on the sole spare parts; indeed, spare pieces are feasible to be treated separately with respect to the whole yacht product, in their production phase, use phase, assumed to be the lifetime of the yacht, and in their end-of-life treatments, with a view to a subsequent life cycle assessment on the parts at issue.

In order to simplify and better fit the real data, it is chosen to concentrate the attention

on a single spare piece of the model SD90/s: the T-Top.
The latter is the upper structural part of the yacht, it consists in a stiff roof protecting the cockpit of the flybridge, sustained by two legs, which incorporate two peaks of storage; it is usually open to create a large seating area with a panoramic view of the sea.

Figure 3.9: SD90/s T-Top.

The main precursor of T-Top is the Hard Top, a similar structure with a rigid roof sustained by two esternal legs. The innovation accomplished by Sanlorenzo was to create a standing structure with internal legs, which leave a high amount of roof surface overhang. The latter, need to sustain and bear not only its own weight, but also vibrations experienced during sailing and wind force that could act on the extended roof surface, generating high pressures on it. In order to study the correct lamination sequence for the different parts constituting the T-Top, Sanlorenzo Technical Department performed a Finite Element Analyis on the structure, which led to the determination of the optimized weight with the best mechanical outcome possible.

3.2.1. Materials and lay up sequences

The whole SD90/s spare pieces production is based on composites lay-up: the transformation technologies aimed at their fabrication are hand lay-up and resin infusion. For what it concerns T-Tops, Sanlorenzo's processing technique is chosen to be the latter: between the main advantages of resin infusion there are a simple textiles layup and an optimization of the weight, since the selected technology allows to reach high fiber concentration ratios with respect to the total laminate.

SD90/s T-Top's lamination sequence is variable in the whole surface of the components constituting the product: it differs depending on the complexity of the shapes, generally planar surfaces are designed to be in sandwich, while turns, changes in shapes are designed to be in solid laminate.

Materials chosen for the production of the laminated manufact are carbon fibres textiles impregnated with epoxy resin and a PVC core of 25 mm of thickness. Physical properties of the single laminae used to manufacture the T-Top are listed in Table 3.1: the following were evaluated by Sanlorenzo's Research&Development laboratory.

	Reinforcement weight	**Laminate thickness**	**Laminate weight**	**Impregnation ratio**
	(g/m^2)	(mm)	(g/m^2)	(%)
RC 200	200	0.23	333	60
RC 400 0°-90°	400	0.46	667	60
XC 411 ±45°	400	0.42	620	64

Table 3.1: Single laminae properties for SD90/s T-Top lamination.

All of the materials used, with the actual quantities exploited, will be responsible for a given share of emissions, with respect to the total production process of a SD90/s T-Top. Their production and treatment will be the first step of LCA that will be performed in order to quantify the environmental footprint of the production of the whole product.

3.3. Life Cycle Assessment

Life-Cycle Assessment methodology evaluates the environmental burdens associated with a product, process or activity, by identifying and quantifying energy and materials used and wastes, in order to assess the impact of those resources, their use and what they release into the environment.
The assessment includes the entire life-cycle of the product, process, or activity, encompassing extracting and processing raw materials, manufacturing, transportation and distribution, use, re-use, maintenance, recycling, and final disposal.
The further aim of this practice is to identify and evaluate opportunities to affect environmental improvements, acting on raw materials and production technologies.

In the current paper, LCA will quantify the environmental impacts of the sole production phase of SD90/s T-Top, therefore its categorization will be *cradle-to-gate*. The latter classification states the boundaries of the study, which are selected to be the starting point of the production (namely the extraction of raw materials and their processing steps) and the factory gate, represented by the conclusion of the component realization.

Firstly, goal and scope of the analysis must be defined, in order to fix the focus of the study, as well as the system boundaries, namely the edges of the considered assessment. Hence the following step is the inventory phase (Life Cycle Inventory, LCI), in which all the data regarding the processes in the system boundary are gathered. The latter are employed in the following phase of LCA, which involves the compilation and quantification of inputs and outputs for a product throughout its life cycle, Life Cycle Impact Assessment (LCIA), where different emissions are sorted into different categories depending on which impact category they contribute to.

Also the main assumptions made in data collection and system building are at this stage summarised: the latter are important to the aims of the current studies, since they can strongly affect the analysis, but are yet essential since reality as it is has many different variables which are extremely difficult to model.

3.3.1. Goal and scope definition

The main goal of the current study is to analyse, quantify, understand and evaluate the potential environmental impact caused by the processes of production of SD90/s T-Top.

System boundaries

The present paper, according to the aforementioned project aims, analyses the life cycle of the products with a *cradle-to-gate* approach, considering the following macro areas of the production:

- procurement, transport and processing of raw materials as well as processing of secondary raw materials serving as inputs;
- production of the composite parts.

Functional unit

The functional unit of the LCA is the quantified performance of a product system for use as a reference unit: in the current case it is chosen to be a SD90/s T-Top, expressed as total mass of the component (kg).

Assumptions and limitations

As stated before, assumptions made in Life Cycle Assessment modelling are essential to facilitate the complex analysis of reality, despite these being approximations that will eventually alter LCA results, at a given extent.

A first assumption concerns the division of the pieces that constitute the T-Top: they are multiple pieces that are bounded together after resin infusion processes, by structural adhesives and composite joints. For simplicity, in this study, the whole structure is assumed to be coming from a single infusion process.

Moreover, the production of moulds and relative models is not considered in the LCA analysis. Theoretically the impacts related to the production of models and moulds should be subdivided for the total amount of pieces produced with the existing moulds. In the presented case, an estimation of the products coming from the same moulds should be made, then impacts related to the production of moulds and models should be evaluated with separate LCAs.

Some of the materials used are not quantified in the technical drawings provided to the production, they are assumed to be used, within normatives and regulations, in limited amounts. Due to lack of data, with respect to quantities actually used - considered as irrelevant - and environmental impacts, those restricted-quantities products will not be considered in the current LCA.

3.3.2. Life cycle inventory analysis

Lyfe cycle inventory analysis is defined by ISO as the ‘phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle’. The inventory relates to the compilation of various environmental inputs and outputs involved in the life cycle of a product. LCI analysis requires quantification of the following elements:

- energy requirements
- raw material needs
- atmospheric emissions
- waterborne emissions
- emissions to land
- solid wastes
- other releases to the environment.

In practice, inventory analysis translates to data gathering and analysis. The process of gathering data entails documenting the pertinent inputs and outputs of a process or product’s life cycle.

LCI is the most demanding phase in LCA, since it requires a large collection of data, which may be difficult to fulfil, since a typical life cycle of a product or service covers thousands of human activities, each of which needs to be understood and recorded in terms of relevant material and energy flows to the environment. This information can usually not be gathered within each specific LCA project due to the high cost of primary data collection. Thus, it is common practice to focus data collection efforts on selected activities that reflect the immediate space for action—these activities are together called the foreground system—and to use generic data from Life Cycle Inventory databases to model the remaining activities, called the background system.

In the current work, it was selected an new tool for LCAs, created by the Association of the European Composite Industry, specifically for composite products manufacturers: Eco Impact Calculator. Its main features and methodologies will be outlined in the next sections of the present work.

3.4. Eco Impact Calculator for Composites

The European Composites Industry Association has recently developed a tool, Eco Impact Calculator, for quickly and easily evaluating the main environmental impacts related to the production processes of the composites components following the cradle-to-gate scheme, which takes into account raw materials production, transport to the production sites and the component production.
The analysis of the environmental impacts are performed by means of a large database related materials and transformation technologies which has been developed from a co-operation among European institutions, research centres and industry throughout several years. This information, accessible from the user, allow to calculate the Life Cycle Assessment of any component in only two steps: first, the choice of the production process and secondly, the composition of the composite material (kind and quantities of the raw materials used for the composite production).

The list of the resources to be kept into account in the cradle-to-gate analysis for a composite material is considerably long. Indeed, not only information about fibers and matrices are required, but also on the fillers, basis materials and coatings, additives and on process auxiliary materials. Other data are related to the process, such as energy and water usage, emissions and by-products.

The output of the tool is available in an Eco Report which contains the results of the environmental impact calculations in three indicators according to three impact assessment methods: Carbon footprint (kg. CO2 eq.), Cumulative Energy Demand (MJ) and ILCD (16 impact categories).

3.4.1. Input

There are two different types of input for the tool. User input and input data. User input is described as the technical information of composite product manufacturing, and

is provided by the users of the tool. The input data for the tool is two-sided. On the one hand there is the data for the conversion processes themselves, and on the other there is the data on the materials. For the materials, 1 kg is modelled based on the available processes in the EcoInvent database enriched through expert judgement and literature. The materials were thereafter run through LCA software for three different assessment methods: The GHG protocol, Cumulative Energy Demand and International Reference Life Cycle Data System (ILCD). The results are transferred to the tool library (materials section).
For the conversion processes, 17 processes have been identified that are able to cover most of the composite manufacturing companies in Europe. Due to the limitations relating to confidentiality and unexpected low data submission, for 5 processes enough questionnaires or industry data were received to be part of the first version of the tool. 3 processes have been modelled on basis of process analysis for energy and in comparence with existing EcoInvent process data the other impact categories. The data delivered are on energy use, waste, emissions excluding the materials, since these are separately provided in the materials database. The units for the data (e.g. kWh electricity) are also pre-calculated through LCA software for three different assessment methods. The results are transferred to the tool library (conversion processes section), and in the tool are multiplied by the average "score" for each unit to enable the user to calculate the environmental impacts of a specific process. The tool is structured this way in order to allow the user to input their own data as well for any conversion process they like.

At this stage, the three steps constituting Eco Impact Calculator for Composites tool will be described and completed with the information regarding the manufacture of the product at issue, the T-Top of Sanlorenzo's SD90/s.

3.4.2. Step one: Define product

The first step is to identify the product. The name that is given to the product will be used as the name of the saved product. The "Total weight product (kg)" block requires the total weight of the finished composite part, so without cut-off material and materials that are used in the process but are not part of the finished product.

There is also the option to define a semi-finished product or intermediate material:

- Finished product: product of which the final Eco Report will be prepared in this tool

- Semi-finished product: product that can be used to run another calculation in this tool, for example a part that needs to be painted or requires a second conversion step
- Intermediate material: intermediate material that can be used to run another calculation in this tool, such as SMC (sheet moulding compound), BMC (bulk moulding compound) or injection moulding compound

At our purpose, the name of the product will be "T-Top SD90/s" and the total weight of the component is of 972 kg, value taken from measurements of the first T-Tops of SD90/s produced in 2022. It is categorized as a finished product and depicted as follows:
"SD90/s T-Top is a complex composite product, constituted by three main structural elements, produced by Sanlorenzo Yacht Shipyards in the production site of Massa (MS). The whole component has some zones of its volume composed of a monolithical structure and others of a sandwich structure, constituted of carbon fiber textiles and expanded polyvinylchlo-ride core impregnated with Vinylester resin through Resin Infusion technique."

3.4.3. Step two: Choose conversion process

The Eco Impact Calculator tool allows to choose between three different options regarding the conversion process which is used to produce the composite product. The tool contains a pre-defined number of processes that are retrieved from the input from different EU producers of composite parts. If it is needed to use data from a particular production facility, such as Sanlorenzo's, it is possible to import the specific dataset for the selected transformation technology. Finally, if no conversion process would be taken into account, the third option allows to not consider it. In the latter case the result of the calculation will be limited to the chosen materials and exclude the contribution of the conversion process.

The following processes are currently included in the tool:

- Pultrusion
- Resin infusion (RI)
- Resin transfer moulding (RTM)
- SMC compounding
- SMC compression moulding

- Thermoplastic compounding
- Long Fibre Thermoplastics compounding
- Thermoplastic injection moulding

The selected process for SD90/s T-Top Sanlorenzo is Resin Infusion (RI).
Resin infusion is the process whereby resin is drawn into a dry laminate whilst it is held under vacuum against a rigid mould by a sealed flexible membrane. The most commonly used membrane consists of a disposable film (vacuum bag) and this film is sealed against the mould edges using a sealant tape.
Resin infusion is particularly relevant when making very large structures as tooling costs are relatively low. The surface finish of the resulting laminate in contact with the membrane is not controlled cosmetically but excellent laminate properties can be achieved. Volatile emissions can also be dramatically reduced making resin infusion an excellent alternative to large-scale open moulding.

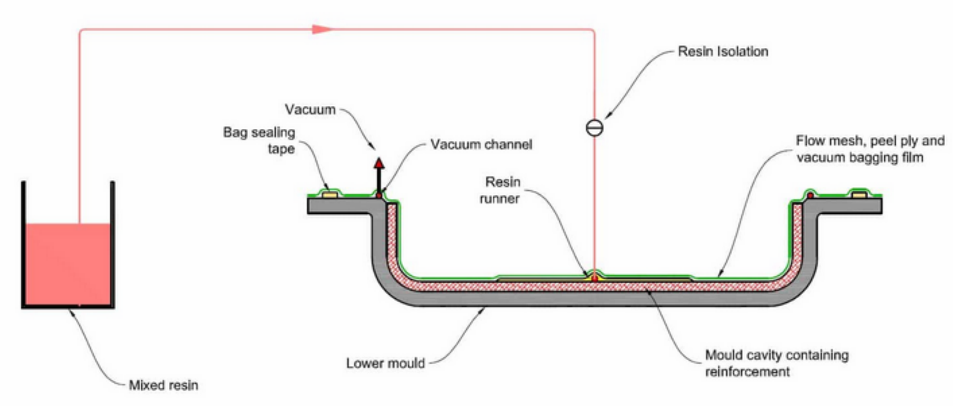


Figure 3.10: Schematic representation of resin infusion process.

As a whole, RI processes for the production of SD90/s T-Top are multiple: the different parts are moulded in separate moulds and joined at a later stage. In the roof of the T-Top, on the laminate internal shell, structures are laminated in order to give structural stability to the component: they consist in an expanded polyurethane core, laminated with carbon fiber textiles. Onto the structures a certain amount of structural Vinylester adhesive is placed, in order to join the two shells together once assembled: the lower part, inside its own moulds is rotated and placed on top of the upper part, as well in its moulds. After the complete polymerization of the structural adhesive the component is extracted by the moulds and the two parts are assembled by perimetral joining lamination.

As mentioned, T-Top is a complex assembly of closed and hollow structures, which is made by the composition of multiple moulds, in order to facilitate composition and extraction. Here are presented the three components, with their moulds compositions, respectively:

- Roof
    - Top mould
    - Roof mould

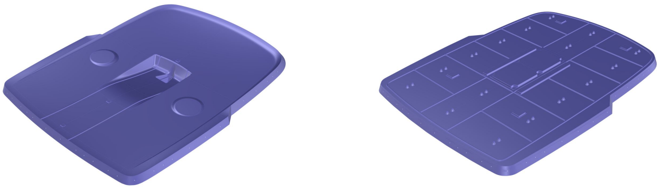


Figure 3.11: T-Top roof moulds decomposition.

- Starboard side T-Top Leg
    - Stern leg mould
    - Amidship leg mould
    - Bow leg mould
    - Base leg mould

Figure 3.12: Starboard side T-Top leg moulds decomposition.

- Port side T-Top Leg
    - Stern leg mould
    - Amidship leg mould
    - Bow leg mould
    - Base leg mould

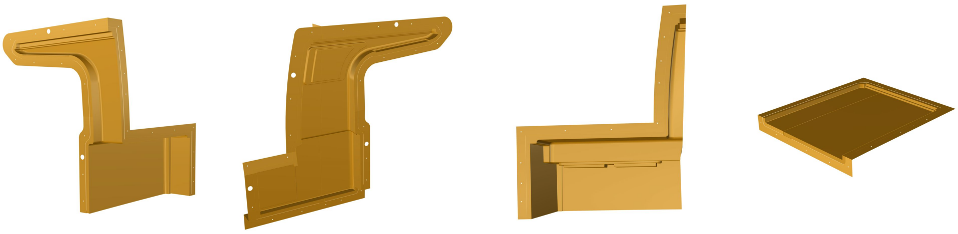


Figure 3.13: Port side T-Top leg moulds decomposition.

3.4.4. Step three: Create recipe

The last input section of the Eco Impact Calculator requests the complete list of the materials constituting the final composite part, equipped with quantities. This section sets the basis for the calculation of the impacts associated to the production of raw materials.

In the calculator, materials are divided into nine categories, here presented:

Category	**Material**
Additives	Accelerator
	Flame Retardants-ATH
	Flame Retardants-Di Ammonium Phosphate
Auxiliaries	Methyl Ethyl Ketone
	PA Plastic Film
	Release Agent
	Acetone
Coating	Gelcoat
	Top Coat-Primer
Core	Balsa
	PET
	PIR
	PVC
Fiber reinforcement	Glass Fiber Assembled Roving
	Glass Fiber Dry Chopped Strands
	Glass Fiber Direct Roving
	Glass Fiber Wet Chopped Strands
	Glass Fiber mats
	Carbon Fiber

Filler	ATH
	Calcium Carbonate
	Sand
	Talc
Resin	EP Curing Agent-Ethylenediamine
	EP Curing Agent-Phtalic Anhydride
	EP Resin
	Isocyanate
	PA Resin
	Peroxide
	PET Resin
	Phenolic Resin
	PP Resin
	PU Resin
	UP Resin (unspecified)
	VE Resin (BPA epoxy based)
	UP Resin (DCPD based)
	UP Resin (isophtalic acid based)
	UP Resin (ortophtalic acid based)
	UP Resin (pure maleic)
Intermediate product	SMC/BMC intermediate
Core mat	Core mat - surface enhancer (t=1.5 mm; 90 g=1m^2)
	Core mat - surface enhancer (t=2 mm; 120 g=1m^2)
	Core mat - surface enhancer (t=3 mm; 160 g=1m^2)
	Core mat - flow medium (t=2 mm; 135 g=1m^2)
	Core mat - flow medium (t=3 mm; 180 g=1m^2)
	Core mat - flow medium (t=4 mm; 250 g=1m^2)
	Core mat - flow medium (t=5 mm; 320 g=1m^2)
	Core mat - flow medium (t=6 mm; 345 g=1m^2)

Table 3.2: Eco Impact calculator - raw materials.

For the production of the selected composite product the following materials and quantities are employed, listed in Table 3.3:

Category	**Material**	**Quantity**
Resin	EP Curing Agent-Ethylenediamine	111 kg
Resin	EP Resin	371 kg
Core	PVC	108 kg
Fiber Reinforcement	Carbon Fibre	452 kg

Table 3.3: T-Top's raw materials recipe.

The tabulated quantities comprehend the total supply of raw materials: part of them will constitute scraps of production. In this case the total mass of the components is 7% higher than the completed part mass.

3.4.5. Step four: View Eco Report

The fourth and last phase of the Eco Impact Calculation is the creation of an Eco Report. The latter will be a collection of the inputs selected during the Product definition steps, but mostly it will gather the output related to the production of the analyzed composite product.

The information highlighted in the report for the production of one SD90/s T-Top are relative to Carbon Footprint and Energy demand, they are, respectively, 26.9 ton_{CO2-eq} and 560.2 GJ.
Moreover, environmental impacts are fully evaluated by means of the 16 impact categories listed in Table 3.4:

Category	**Amount**	**Unit**
Climate change	$2.69 \cdot 10^4$	kg_{CO2eq}
Ozone depletion	$8.99 \cdot 10^-3$	$kg_{CFC-11eq}$
Human toxicity, non-cancer effects	$1.64 \cdot 10^-3$	$CTuh$
Human toxicity, cancer effects	$3.48 \cdot 10^-4$	$CTuh$
Particulate matter	14.1	$kg_{PM2.5eq}$
Ionizing radiation HH	$3.64 \cdot 10^3$	kBq_{U235eq}
Ionizing radiation E	$3.31 \cdot 10^-2$	$CTUe$
Photochemical ozone formation	79.9	$kg_{NMVOCeq}$
Acidification	$1.28 \cdot 10^2$	$molc_{H+eq}$
Terrestrial eutrophication	$2.47 \cdot 10^2$	$molc_{Neq}$
Freshwater eutrophication	1.58	kg_{Peq}
Marine eutrophication	24.4	kg_{Neq}
Freshwater ecotoxicity	$1.04 \cdot 10^4$	$CTUe$
Land use	$1.27 \cdot 10^4$	$kg_{Cdeficit}$
Water resource depletion	86.5	$m^3_{watereq}$
Mineral, fossil & rne resource depletion	0.171	kg_{Sbeq}

Table 3.4: Environmental impact expressed in categories calculated with ILCD 2011 midpoint+ (v1.06) methodology.

Eco Report is displayed in Appendix A: "SD90S T-Top".

3.4.6. Results discussion

A first comment about the results presented in Section 3.4.5 concerns the two main unit processes constituting the LCA: raw materials production and composite component manufacturing.

The first one accounts for the 95% of the total environmental burdens caused by the composite component production, as seen graphically in Figure 3.14.

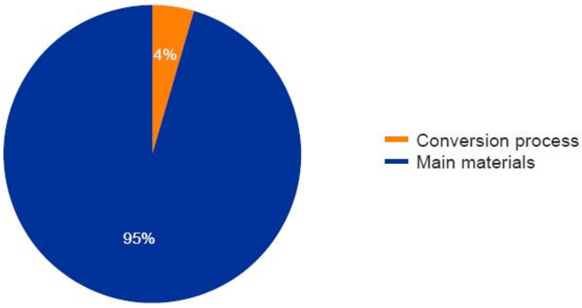


Figure 3.14: Subdivision of environmental impacts for the production of the T-Top.

Thus, in order to improve the environmental performance of the T-Top production, the following sections will analyze the impact output of raw materials selection. An new design project with alternative raw materials will be proposed, in order to set the bases for a new design methodology, which will take into account the environmental performances of the analyzed structural part.

4 | T-Top Life Cycle Engineering

Traditionally, the workflow for the design of a structural product used to concern technical performances and durability; the latter were the main requirements for a proper design project.

A new goal of engineering design is nowadays becoming established: the practice of including the conception process the sustainability thinking, together with performance and durability: it is called Life Cycle Engineering (LCE).

LCE is a new concept of design that includes product vision, structure, materials, processes in view of an environmental friendly product. The introduction of LCA has provided designers with the ability to gather and model detailed information regarding the environmental impact of a product system earlier in its conceptual development, and incorporate this information in the design process. [14]

4.1. Alternative raw materials design

In order to improve the environmental performance of the selected composite component, more environmentally friendly alternatives should be examined.

An effective alternative to carbon fibers, for example are glass fibers: as mentioned in Chapter 2, their availability, cost and mechanical performance make glass fibres a feasible substitute to carbon fibers. Their production process employs a minor amount of resources and emits lower quantities of CO_2. Mainly for economical reasons, glass fibers are widely employed in the nautical sector: Sanlorenzo's production is almost entirely connected to the use of glass reinforced polymer composites, starting from the production of the hulls, completely made of glass fibers, vinylester resin and expanded PVC as core material. Thus this conversion of the selected T-Top into a glass-fibre manufacture product would be in the production standards of the company, therefore the conversion would be applicable without subverting production processes or raw materials supplies for the company.

Composite design is intrinsically bounded to the physical nature of the constituents creating the material, therefore the conception of a new structural component with the same purpose as the original one will need an appropriate structural redefinition in terms of lamination sequence and fiber-textiles selection.

4.1.1. Structural conversion

A large portion of a product design, from an engineering point of view, consists in the evaluation of the structural constraints and loads acting on the desired part, in order to structure it in an efficient perspective.
When working with composite materials, this stage of design is crucial in order to conceive a lamination sequence suitable to sustain the desired loads, since composite engineering strongly depends on the structural purpose of the product at issue.

In the present work a structural analysis is performed in order to convert the Carbon-Epoxy T-Top into a Glass-Vinylester one: since mechanical properties of the constituents differ, also the design must be updated. The goal of the conversion is to keep intact the structural performances of the component, in terms of deformations and stresses. This results into keeping the mechanical properties of the laminates constituting the T-Top equivalent.

Some assumptions were made in view of a coherent redefinition of the layup sequence: firstly the symmetry of the laminate should be kept unchanged, as well as the types of textiles employed (biaxial 0°-90°, biaxial ±45°, uniaxial).
Typical materials used in Sanlorenzo products include several textiles types of glass fibers combined with vinylester resins: therefore, iteratively, making use of a Finite Element Method software, it was found the most suitable layup sequence which could match the mechanical performances of the original carbon-fibre laminate.

Two different laminates were tested, the two main constituents of the T-Top: a monolithic laminate and a sandwich one, whose layup sequences are listed respectively as follows:

$$[RC200/RC400(0^\circ - 90^\circ)/XC411(\pm 45^\circ))_{2s}] \tag{4.1}$$

$$\begin{aligned}&[RC200/RC400(0^\circ - 90^\circ)/XC411(\pm 45^\circ)/PVC/\\&XC411(\pm 45^\circ)/RC400(0^\circ - 90^\circ)]\end{aligned} \tag{4.2}$$

The two laminates, shaped as a square panel, were tested with finite element method in bending and their maximum displacements were recorded. The latter were compared to the output generated by the FEM tests on new laminates, constituted by glass-vinylester laminae.

Constraints and loads are represented in Figure 4.1. They are respectively a fixed constraint on the perimeter of the panel and a distributed load on the entire surface.

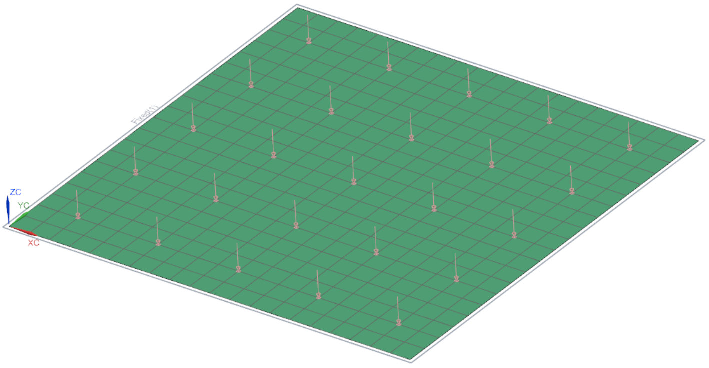


Figure 4.1: Graphical representation of load and constraints for the selected panel.

The resulted nodal displacements for the two kinds of panels were 12.85 mm for the solid laminate and 0.175 mm for the sandwich one (Figures 4.2 and 4.3).

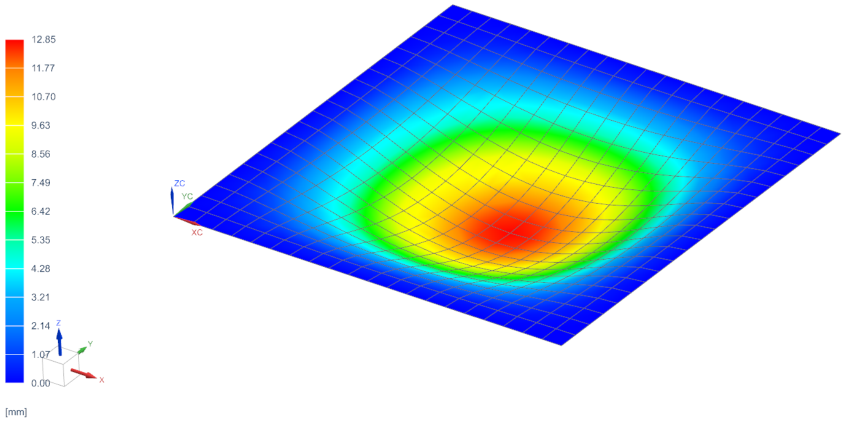


Figure 4.2: Nodal displacements for single skin carbon-epoxy laminate.

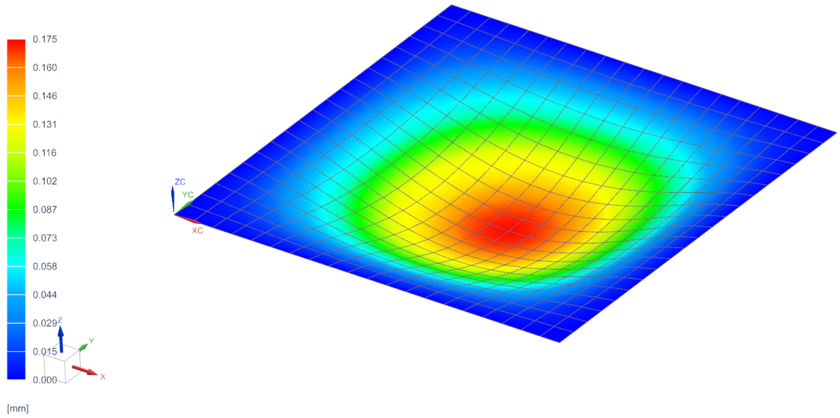


Figure 4.3: Nodal displacements for sandwich carbon-epoxy laminate.

In order to match the original laminates properties and performances, different combinations of glass-vinylester laminae were employed iteratively in the FEM software, until reaching an equal or better response to the mechanical input.

Eventually the lamination sequences were found with the following textiles, listed in Table 4.1.

	Reinforcement weight	**Laminate thickness**	**Laminate weight**	**Impregnation ratio**
	(g/m^2)	(mm)	(g/m^2)	(%)
MAT 300	200	0.23	333	60
BIAX 0°-90° 800	800	0.63	1062	70
BIAX 0°-90° 1075	1075	0.89	1578	68
BIAX ± 45° 615	600	0.46	831	75

Table 4.1: Single laminae properties for SD90/s T-Top new lamination.

Here are reported the best results of the iterative process, the new optimized resulting lamination sequences are found to be the following, the first one for the single skin laminate and the second one for the sandwich structure:

$$[MAT300/(BIAX(0^\circ - 90^\circ)800/BIAX(\pm 45^\circ)615/BIAX(0^\circ - 90^\circ)1075)_s] \tag{4.3}$$

$$\begin{aligned} &[MAT300/BIAX(0^\circ - 90^\circ)800/BIAX(\pm 45^\circ)615/PVC/ \\ &\qquad BIAX(\pm 45^\circ)615/BIAX(0^\circ - 90^\circ)800] \end{aligned} \tag{4.4}$$

Figures 4.4 and 4.5 report the output in nodal displacements of the FEM analysis: single skin laminate's maximum deflection is 8.55 mm, while sandwich laminate's maximum displacement is 0.169 mm, both of them improving the original materials performances.

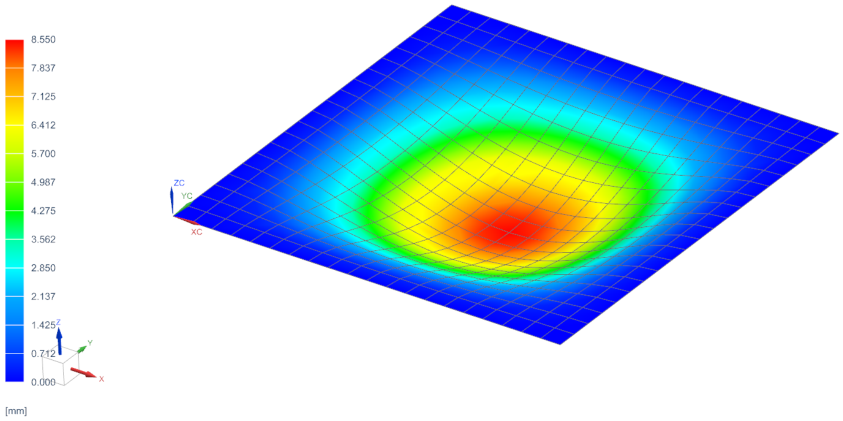


Figure 4.4: Nodal displacements for single skin glass-vinylester laminate.

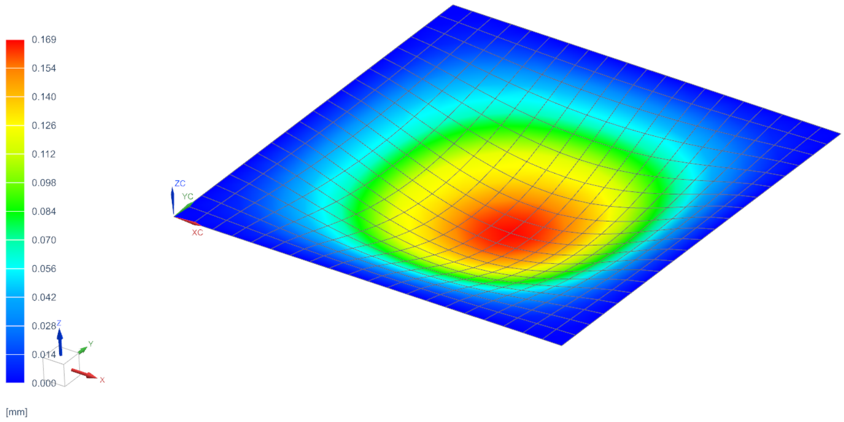


Figure 4.5: Nodal displacements for sandwich glass-vinylester laminate.

In order to confirm the hypothesized layup sequence, it was performed a finite element analysis on the complete T-Top model.
Previous analyses tested the original T-Top in four different loading cases:

- Load case 1 - 1 kPa applied as wind pressure. (Modeling 80 knots windspeed);
- Load case 2 - 100 kg at two different positions for service, in the backward part of the roof's top;
- Load case 3 - 100 kg at two different positions for service, in the forward part of the roof's top;

- Load case 4 - 1.5 G transversal acceleration and 1 G forward acceleration.

Among those four, the assessed most critical one was the second one, two distributed loads on delimited areas of the roof's top backward part. Therefore the load case with which the newly designed T-Top was tested was the latter.
For what it concerns constraints, the T-Top is considered bounded with a rigid joint on the bases and on the external sides of the legs' peaks. As well as the roof, which is tied to the legs by means of fixed joints.
Loads and boundary conditions are depicted in Figure 4.6.

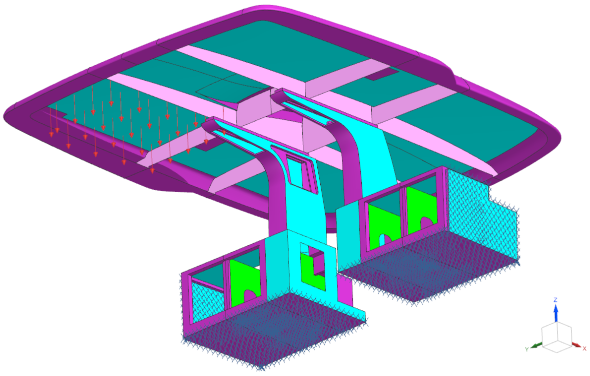


Figure 4.6: Graphical representation of load and constraints for the modelled T-Top.

The analysis performed gave the expected results, as depicted in Figures 4.7 and 4.8: the maximum displacements are 13.90 mm and 11.19 mm, respectively for the carbon-epoxy T-Top and the glass-vinylester T-Top.

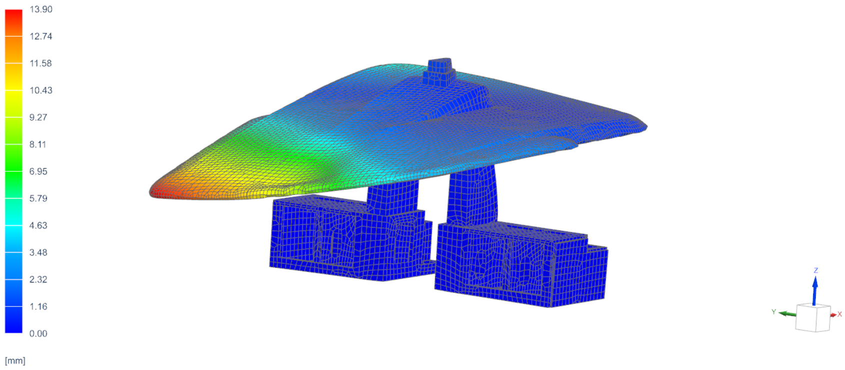


Figure 4.7: Nodal displacements for the complete carbon-epoxy T-Top.

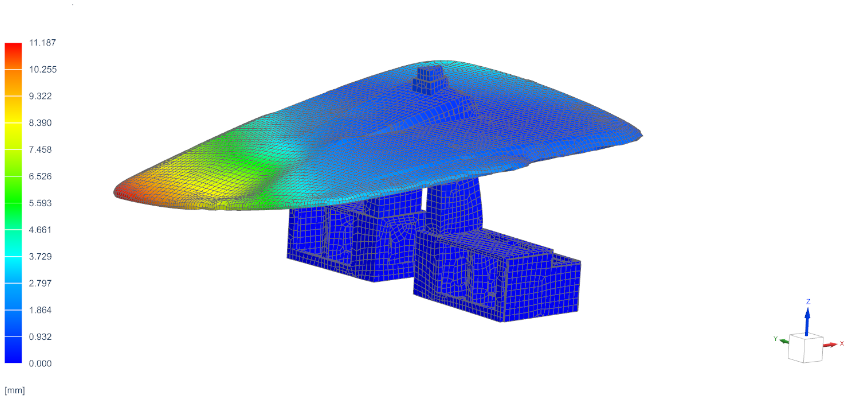


Figure 4.8: Nodal displacements for the complete glass-vinylester T-Top.

The newly designed laminate's performances exceed the original laminate ones, therefore the structural properties are matched in excess; in order to better suit the original mechanical properties, new glass textiles, with lower basis weights, could be evaluated and chosen. This would be beneficial also for the total weight optimization.

By defining the new lamination sequence, a new set of raw materials and quantities is defined and calculated, ready to run a new Life Cycle Assessment on the glass-vinylester component.

4.1.2. Eco Impact Analysis on GRP T-Top

In order to evaluate the environmental impacts of the newly designed T-Top, the quantities of the current raw materials were computed and the inputs included in the "Create recipe" section of the Eco Impact Calculator for composites.

The new recipe is created as summarized in Table 4.2:

Category	**Material**	**Quantity**
Resin	VE Resin (BPA epoxy based)	913 kg
Core	PVC	108 kg
Fiber Reinforcement	Glass Fibre Assembled Rovings	778 kg
Fiber Reinforcement	Glass Fibre (mats)	42 kg

Table 4.2: T-Top's new raw materials recipe.

The output created by the tool is a new Eco Report, which records the environmental impact of the production of a glass-vinylester T-Top by means of environmental impact categories, collected in Table 4.3. Carbon Footprint and Energy demand result respectively, 9.26 ton_{CO2-eq} and 170.6 GJ.

Category	**Amount**	**Unit**
Climate change	$9.17 \cdot 10^3$	kg_{CO2-eq}
Ozone depletion	$7.65 \cdot 10^-4$	$kg_{CFC-11-eq}$
Human toxicity, non-cancer effects	$7.88 \cdot 10^-4$	$CTuh$
Human toxicity, cancer effects	$1.95 \cdot 10^-4$	$CTuh$
Particulate matter	8.15	$kg_{PM2.5-eq}$
Ionizing radiation HH	$2.54 \cdot 10^2$	$kBq_{U235-eq}$
Ionizing radiation E	$8.93 \cdot 10^-3$	$CTUe$
Photochemical ozone formation	47.6	$kg_{NMVOC-eq}$
Acidification	47.0	$molc_{H+-eq}$
Terrestrial eutrophication	$1.08 \cdot 10^2$	$molc_{N-eq}$
Freshwater eutrophication	0.302	kg_{P-eq}
Marine eutrophication	10.3	kg_{N-eq}
Freshwater ecotoxicity	$2.06 \cdot 10^4$	$CTUe$
Land use	$4.39 \cdot 10^3$	$kg_{C-deficit}$
Water resource depletion	19.8	$m^3_{water-eq}$
Mineral, fossil & rne resource depletion	0.142	kg_{Sb-eq}

Table 4.3: Environmental impact expressed in categories calculated with ILCD 2011 midpoint+ (v1.06) methodology.

New Eco Report is displayed in Appendix A: "SD90S T-Top - GRP".

According to the results, for the production of a glass fiber-vinylester T-Top the 81% of the total emissions are allocated to raw materials extraction, transportation and processing, while the remaining part to the production process of the composite component (Figure ??.

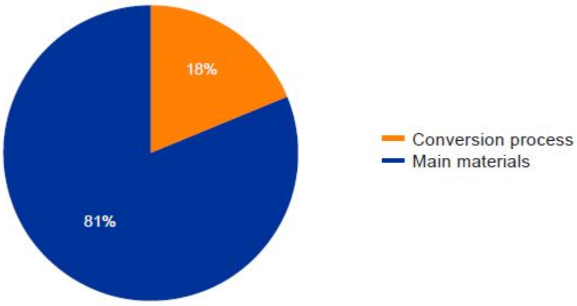


Figure 4.9: Subdivision of environmental impacts for the production of the new T-Top.

4.2. Results discussion and comparison

Once having collected all the information resulted from the LCE analysis, results of the two life cycle assessments were compared, mainly in terms of environmental impacts (environmental indicators, Carbon footprint, energy demand) and also with side considerations regarding costs and weight of the component.

For what it concerns the environmental indicators, the following graph depicts the relative differences between the two products, chosen a few, representative, categories among the 16:

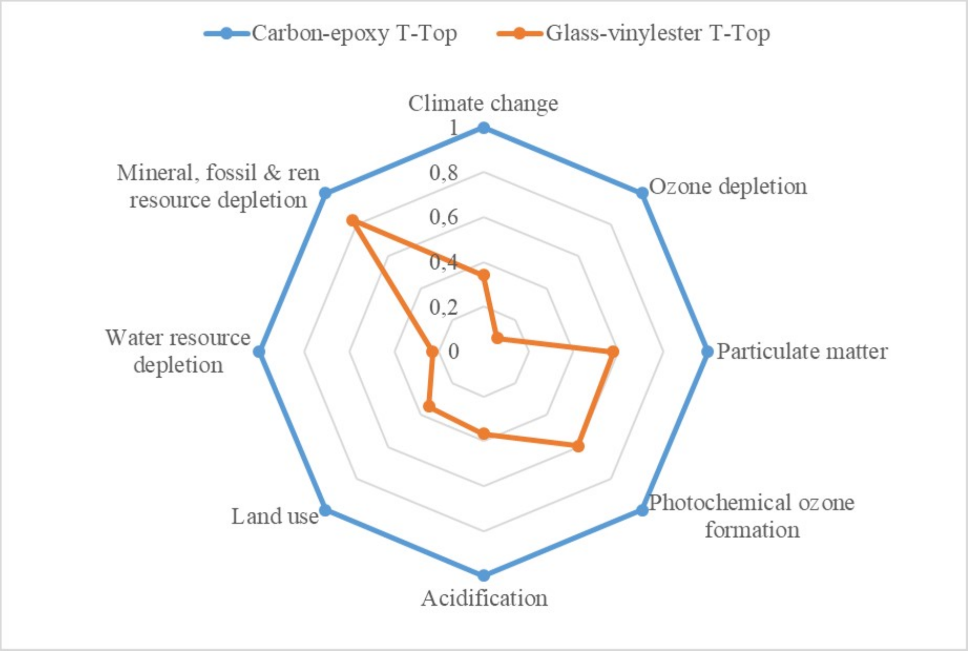


Figure 4.10: Relative values of environmental impact indicators for the different T-Tops.

It appears that the employment of glass-fiber reinforced polymers strongly reduces the impact on environment.

By comparing the products in terms of Carbon footprint and Energy demand, the differences in raw materials selection cause a decrease in the aforementioned quantities of, respectively, 65% and 70%. The first value could be explained by the differences in CO_2 quantities released in the processes of production of the two fibers kinds.
The large difference in Energy demand is mainly due to considerable amount of energy needed by the steps of fibres production: the production technique for carbon fibres require high temperatures and loads to be applied to the original polymeric fibres, in order to create their full-carbon structure and their strongly oriented molecular morphology.

In view of a complete assessment on the produced component, it is performed a brief analysis on the difference in costs of the two T-Tops: the one produced with carbon fibers and epoxy resins have an estimated cost - raw materials only - of nearly €19500, while the glass fiber-vinylester one has raw materials costs around €7500.
The last important aspect evaluated in this work is the change in weight between the two components: the newly designed T-Top results 40% heavier than the original one. This outcome represents a drawback to the implementation of the new design, since higher weights are directly connected to an increase of fuel needed to move the craft, other than an growth of the yachts instability.

Graphically the comparisons discussed are represented in the following graphs:

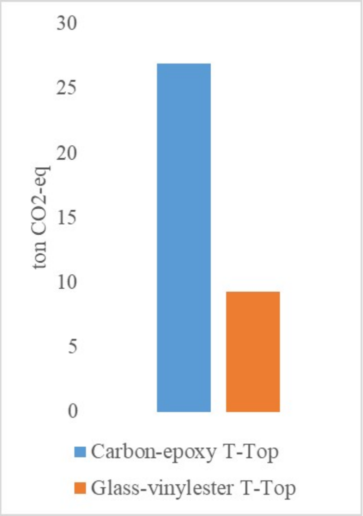


Figure 4.11: LCA results comparison: Carbon footprint (ton_{CO_2-eq})

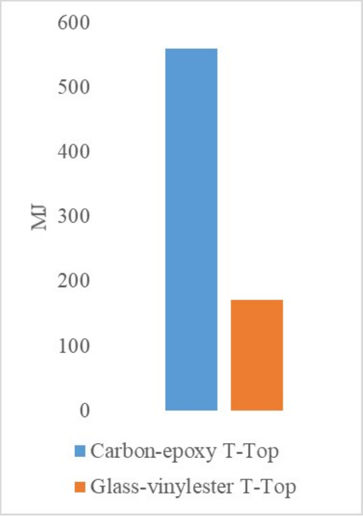


Figure 4.12: LCA results comparison: Energy demand (MJ)

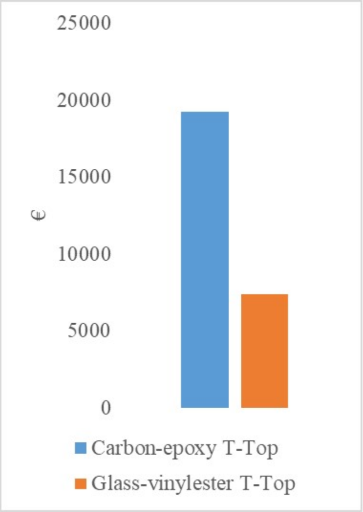


Figure 4.13: LCA results comparison: Raw materials cost (€)

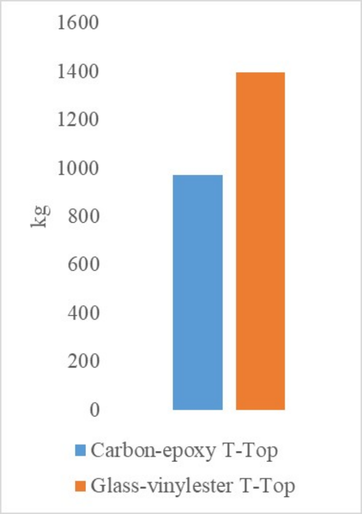


Figure 4.14: LCA results comparison: Weight (kg)

5 | Conclusions

The aim of the present work was to include sustainability practices in composite component design in yacht industry. In order to account for sustainability in the workflow of the creation of a composite component, it was selected a method to quantify the environmental impacts: Life Cycle Assessment. The latter, for the purpose of the current study, was based on the cradle-to-gate approach, which comprehends the two most important steps in a component creation: extraction, processing, transport of raw materials and transformation techniques for the realization of the component.

A functional approach to make this workflow exploitable was found in restricting the analysis to a single component of SD90/s motor yacht, a new recreational craft line of Sanlorenzo, leading shipyard in composite yacht production.
The component chosen for the analysis was a structural resin-infused carbon-epoxy T-Top, a stiff roof protecting the cockpit of the boat's flybridge. The hypotheses and conclusion drawn from the analysis could be potentially extended to larger volumes of composites produced, achieving the scaling ability of the proposed design methodology.

Once having assessed the environmental impacts of the production of the original T-Top, there were evaluated raw materials substitutes to the original carbon-epoxy constituents, which would potentially score lower impact values on the complete LCA.
The most feasible alternatives were found to be glass-vinylester laminates, due to their availability on the market, stability in mechanical properties and durability, all of these characteristics were evaluated in relation to yacht industry and marine environment.
In order to assess the environmental behaviour of the new component, a prior structural study was performed in order to match mechanical stability of the original T-Top, by means of finite element method simulations. All the design steps follow the practice of Life Cycle Engineering, which comprehends LCA and fully Once the new quantities of raw materials had been estimated, the LCA could be carried out, by keeping unchanged the production technique. The latter confirmed the initial hypotheses of an improvement

in CO_2 emissions and energy demand, along with the global environmental indicators.

Other considerations were conducted between the original component and the newly designed one, about difference in costs and weight: the sustainable alternative appears to be more convenient in terms of expenses, while the original one suited better the project demands in terms of lightness. The last aspect is the most relevant in terms of applicability: a heavier structure in a motor yacht would necessarily mean greater amounts of energy to be employed for the cruising of the boat, for which gasoline fuel is used, intrinsically negative in terms of environmental damage effects.

In conclusion, from a cradle-to-gate analysis the proposed alternative would reduce the environmental impact of the selected component. However, in order to provide a fully developed environmental assessment, also use phase and end of life of the component should be modelled. The latter require great amount of data and many parameters entering the analysis.
The future perspective to this work could concentrate onto gathering data about end of life treatments, new raw materials (especially constituents for biocomposites) and materials conversion process data specific to companies processes.
These new data will make LCE calculations more and more precise, in order to give results and estimations compliant with reality and making LCE the reliable methodology for the design with composite components.

Bibliography

[1] Holm Altenbach, Johannes Altenbach, and Wolfgang Kissing. Mechanics of composite structural elements second edition.

[2] T. P. Sathishkumar, S. Satheeshkumar, and J. Naveen. Glass fiber-reinforced polymer composites - a review, 2014.

[3] Yu I Kolesov, M Yu Kudryavtsev, and N Yu Mikhailenko. Science for glass production types and compositions of glass for production of continuous glass fiber (review), 2001.

[4] Antal Dér, Alexander Kaluza, Denis Kurle, Christoph Herrmann, Sami Kara, and Russell Varley. Life cycle engineering of carbon fibres for lightweight structures. volume 69, pages 43–48. Elsevier B.V., 2018.

[5] Felice Rubino, Antonio Nisticò, Fausto Tucci, and Pierpaolo Carlone. Marine application of fiber reinforced composites: A review, 2020.

[6] William D Callister Jr and David G Rethwisch. *Fundamentals of materials science and engineering: an integrated approach.* John Wiley & Sons, 2020.

[7] Rees D Rawlings. *Composite materials: engineering and science.* Woodhead Publishing, 1999.

[8] N Mohd Nurazzi, A Khalina, SM Sapuan, AHAM Dayang Laila, M Rahmah, and Z Hanafee. A review: Fibres, polymer matrices and composites. *Pertanika Journal of Science & Technology*, 25(4), 2017.

[9] Zhuang Li and Malcolm J Crocker. A review on vibration damping in sandwich composite structures. *International Journal of Acoustics and Vibration*, 10(4):159–169, 2005.

[10] M. Ramesh, K. Palanikumar, and K. Hemachandra Reddy. Mechanical property evaluation of sisal-jute-glass fiber reinforced polyester composites. *Composites Part B: Engineering*, 48:1–9, 5 2013.

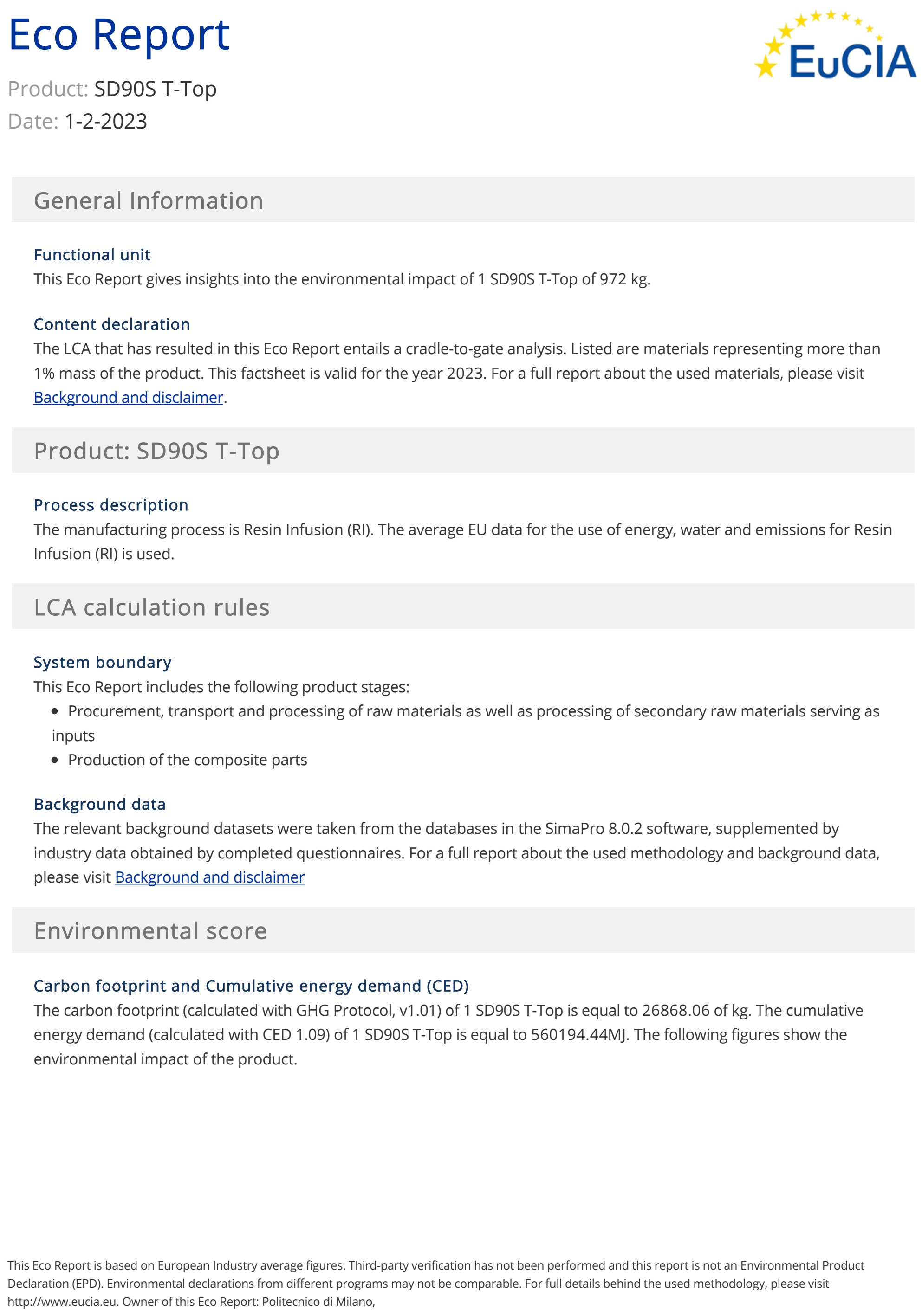
[11] Saira Taj, Munawar Ali Munawar, and Shafi Ullah Khan. Natural fiber-reinforced polymer composites, 2007.

[12] Tamás Deák and Tibor Czigány. Chemical composition and mechanical properties of basalt and glass fibers: A comparison. *Textile Research Journal*, 79:645–651, 2009.

[13] Pablo Resende Oliveira, Michael May, Tulio Hallak Panzera, and Stefan Hiermaier. Bio-based/green sandwich structures: A review. *Thin-Walled Structures*, 177:109426, 2022.

[14] Elcin Aleixo Calado, Marco Leite, and Arlindo Silva. Selecting composite materials considering cost and environmental impact in the early phases of aircraft structure design. *Journal of Cleaner Production*, 186:113–122, 2018.

A | Appendix A



Eco Report

Product: SD90S T-Top
Date: 1-2-2023

General Information

Functional unit

This Eco Report gives insights into the environmental impact of 1 SD90S T-Top of 972 kg.

Content declaration

The LCA that has resulted in this Eco Report entails a cradle-to-gate analysis. Listed are materials representing more than 1% mass of the product. This factsheet is valid for the year 2023. For a full report about the used materials, please visit Background and disclaimer.

Product: SD90S T-Top

Process description

The manufacturing process is Resin Infusion (RI). The average EU data for the use of energy, water and emissions for Resin Infusion (RI) is used.

LCA calculation rules

System boundary

This Eco Report includes the following product stages:

- Procurement, transport and processing of raw materials as well as processing of secondary raw materials serving as inputs
- Production of the composite parts

Background data

The relevant background datasets were taken from the databases in the SimaPro 8.0.2 software, supplemented by industry data obtained by completed questionnaires. For a full report about the used methodology and background data, please visit Background and disclaimer

Environmental score

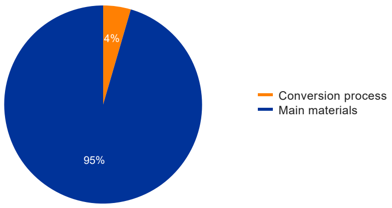
Carbon footprint and Cumulative energy demand (CED)

The carbon footprint (calculated with GHG Protocol, v1.01) of 1 SD90S T-Top is equal to 26868.06 of kg. The cumulative energy demand (calculated with CED 1.09) of 1 SD90S T-Top is equal to 560194.44MJ. The following figures show the environmental impact of the product.

Eco Report

Product: SD90S T-Top
Date: 1-2-2023

Carbon Footprint



Carbon Footprint:

26868.06 kg

Cumulative energy demand:

560194.44 MJ

The International Reference Life Cycle Data Systems (ILCD)

The total score of 1 SD90S T-Top is calculated with the ILCD 2011 midpoint+ (v1.06) methodology.

Category	Amount	Unit
Climate change	2.69e+4	kg CO2 eq
Ozone depletion	8.99e-3	kg CFC-11 eq
Human toxicity, non-cancer effects	1.64e-3	CTuh
Human toxicity, cancer effects	3.48e-4	CTuh
Particulate matter	1.41e+1	kg PM2.5 eq
Ionizing radiation HH	3.64e+3	kBq U235 eq
Ionizing radiation E (interim)	3.31e-2	CTUe
Photochemical ozone formation	7.99e+1	kg NMVOC eq
Acidification	1.28e+2	molc H+ eq
Terrestrial eutrophication	2.47e+2	molc N eq
Freshwater eutrophication	1.58e+0	kg P eq
Marine eutrophication	2.44e+1	kg N eq
Freshwater ecotoxicity	1.04e+4	CTUe
Land use	1.27e+4	kg C deficit
Water resource depletion	8.65e+1	m3 water eq
Mineral, fossil & ren resource depletion	1.71e-1	kg Sb eq

This Eco Report is based on European Industry average figures. Third-party verification has not been performed and this report is not an Environmental Product Declaration (EPD). Environmental declarations from different programs may not be comparable. For full details behind the used methodology, please visit http://www.eucia.eu. Owner of this Eco Report: Politecnico di Milano,

Eco Report

Product: SD90S T-Top
Date: 1-2-2023

This Eco Report is based on European Industry average figures. Thirdparty verification has not been performed and this report is not an Environmental Product Declaration (EPD). Environmental declarations from different programs may not be comparable.

Eco Report

Product: SD90S T-Top - GRP
Date: 9-3-2023

EuCIA

General Information

Functional unit

This Eco Report gives insights into the environmental impact of 1 SD90S T-Top - GRP of 1394 kg.

Content declaration

The LCA that has resulted in this Eco Report entails a cradle-to-gate analysis. Listed are materials representing more than 1% mass of the product. This factsheet is valid for the year 2023. For a full report about the used materials, please visit Background and disclaimer.

Product: SD90S T-Top - GRP

Process description

The manufacturing process is Resin Infusion (RI). The average EU data for the use of energy, water and emissions for Resin Infusion (RI) is used.

LCA calculation rules

System boundary

This Eco Report includes the following product stages:

- Procurement, transport and processing of raw materials as well as processing of secondary raw materials serving as inputs
- Production of the composite parts

Background data

The relevant background datasets were taken from the databases in the SimaPro 8.0.2 software, supplemented by industry data obtained by completed questionnaires. For a full report about the used methodology and background data, please visit Background and disclaimer

Environmental score

Carbon footprint and Cumulative energy demand (CED)

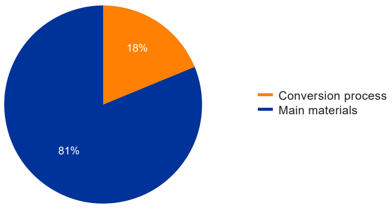
The carbon footprint (calculated with GHG Protocol, v1.01) of 1 SD90S T-Top - GRP is equal to 9255.45 of kg. The cumulative energy demand (calculated with CED 1.09) of 1 SD90S T-Top - GRP is equal to 170625.21MJ. The following figures show the environmental impact of the product.

This Eco Report is based on European Industry average figures. Third-party verification has not been performed and this report is not an Environmental Product Declaration (EPD). Environmental declarations from different programs may not be comparable. For full details behind the used methodology, please visit http://www.eucia.eu. Owner of this Eco Report: Politecnico di Milano,

Eco Report

Product: SD90S T-Top - GRP
Date: 9-3-2023

Carbon Footprint



Carbon Footprint:

9255.45 kg

Cumulative energy demand:

170625.21 MJ

The International Reference Life Cycle Data Systems (ILCD)

The total score of 1 SD90S T-Top - GRP is calculated with the ILCD 2011 midpoint+ (v1.06) methodology.

Category	Amount	Unit
Climate change	9.17e+3	kg CO2 eq
Ozone depletion	7.65e-4	kg CFC-11 eq
Human toxicity, non-cancer effects	7.88e-4	CTuh
Human toxicity, cancer effects	1.95e-4	CTuh
Particulate matter	8.15e+0	kg PM2.5 eq
Ionizing radiation HH	2.54e+2	kBq U235 eq
Ionizing radiation E (interim)	8.93e-3	CTUe
Photochemical ozone formation	4.76e+1	kg NMVOC eq
Acidification	4.70e+1	molc H+ eq
Terrestrial eutrophication	1.08e+2	molc N eq
Freshwater eutrophication	3.02e-1	kg P eq
Marine eutrophication	1.03e+1	kg N eq
Freshwater ecotoxicity	2.06e+4	CTUe
Land use	4.39e+3	kg C deficit
Water resource depletion	1.98e+1	m3 water eq
Mineral, fossil & ren resource depletion	1.42e-1	kg Sb eq

This Eco Report is based on European Industry average figures. Third-party verification has not been performed and this report is not an Environmental Product Declaration (EPD). Environmental declarations from different programs may not be comparable. For full details behind the used methodology, please visit http://www.eucia.eu. Owner of this Eco Report: Politecnico di Milano,

Eco Report

Product: SD90S T-Top - GRP
Date: 9-3-2023

List of Figures

List of Tables