Tallinn University of Technology
SCHOOL OF ENGINEERING
Department of Mechanical and Industrial Engineering

TALLINNA TEHNIKAÜLIKOOL

SUSTAINABLE AND ECO-FRIENDLY SAILING YACHT PRODUCTION

JÄTKUSUUTLIK JA KESKKONNASÕBRALIK PURJEKA TOOTMINE

MASTER THESIS

Student: Karl-Hannes Tagu

Student code: 191687MARM

Supervisor: Tauno Otto, Prof.

Tallinn 2020

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Hereby I declare, that I have written this thesis independently.
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Industrial Engineering and Management

THESIS TASK

Student: Karl-Hannes Tagu (name, student code)

Study programme, MARM06/15, Industrial engineering and management (code and title)

main speciality:

Supervisor(s): Prof. Tauno Otto, +372 530 90 118 (position, name, phone)

Thesis topic:

(in English) *Sustainable and eco-friendly sailing yacht production*

(in Estonian) Jätkusuutlik ja keskkonnasõbralik purjeka tootmine

Thesis main objectives:

1. Finding solutions, making yacht building sustainable and eco-friendly
2. Finding opinions to make yacht more recyclable
3. Evaluating the cost and effect of making yacht as a eco-friendly

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Research different ways to use eco-friendly and sustainable materials	20.04
2.	Update the current lay-up with eco-friendly materials	03.05
3.	Evaluate the costs of using sustainable materials	13.05

Language: English Deadline for submission of thesis: “25”May 2020 y.

Student: …………………….. ....……............. “25”May 2020 y.

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CONTENT

PREFACE

The biggest goal of this thesis is to make the sailboat and its production more eco-friendly, involving the best opportunities available. This thesis use as an example an existing 37-feet long yacht. This work has been born of a longer-term collaboration with Cossutti Yacht Design team. Here I would like to thank Maurizio Cossutti, who gave advice and shared his experience in boat designing and building. In addition, should be thanked Ridas Yacht & Composites for assistance and cooperation.

I believe, this master thesis provides new ideas and thoughts for future projects and sailboat production. I would also like to thank Aivar Tuulberg, who is the owner of the prototype boat, who involved me into that process. Last but not the least should be thanked this work supervisor Tauno Otto for his advice and support while writing this thesis.

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LIST OF ABBREVIATIONS AND SYMBOLS

EPS- Expanded Polystyrene

EOL- End-of-life is a term which, indicating that the product is at the end of its useful life. In pleasure craft sector, it means that boat has reached the end of their useful lives and are out of options how to maintain the vessel usefully.

FRP- fibre-reinforced polymer-based composites

GRP - glass reinforced plastic

MDF- Medium-density fibreboard

PFRP - plant fibre composites

ORC - Offshore Racing Congress

1. INTRODUCTION

The current master thesis aim is to investigate the options to increase the sustainable materials use and green way of thinking in yacht or pleasure craft manufacturing.

Boatbuilding is the industry, what has existed for a thousand years, has a long history, traditions and knowledge. However, more than ever, the boat building industry has been changed a lot in the last decades. It is because of new synthetic materials and computer-aided designs (e.g. computational fluid dynamics), which has done an enormous step forward. It means that these days are over where fathers from generation to generation are inheriting knowledge and skills of material handling in boat building. Nowadays the theology will be improved during a human working life so that workforces and expertise have to be updated on time. The share of composite materials used in the boat building industry has been increased yearly since that time, when composite materials started to replace wooden materials. As for small craft industry building boats of maximum 50 m of length, composite materials are unrivalled with a share of 70%. Fibre-reinforced polymer-based composites (FRP) have significant usage in boat building and marine construction industries in a broader range for decades, because it is the optimum choice in terms of durability, workability and cost. The material itself is resistant to the UV, seawater, fatigue loads and high strength-to-weight ratio, comparing the old conventional materials (Neşer, 2017).

So far, the end-of-life (EOL) disposal has not been a significant issue because composite vessels are highly durable (Marsh, End-of-life boat disposal – a looming issue, 2013). For this reason, the problems with EOL and boat handling in waste management have been practically not evaluated and not wanted to find the best solutions (Serranti, Capobianco, Bonifazi, & Donne, 2016). Some surveys have estimated, that in Europe are 6 million leisure crafts with boat lifespans of 30-45 years, which means ca 140,000 of these vessels per year to be expected to become due for scrapping (Marsh, End-of-life boat disposal – a looming issue, 2013). In low environment impact perspective, the other sectors are a more advanced, for example, is automotive, where design/manufacturing and transnational directives come up with several strategies to apply maximized recycling, minimizing the impact to the environment (Serranti, Capobianco, Bonifazi, & Donne, 2016).

This master thesis is based on a project what started in 2014, when I was involved with performance sailing yacht production. Reason for choosing this topic was because of the background, as sailor and advisor in a yacht-building project. I have experience in the pleasure craft manufacturing as owner surveillance of different projects.

In this thesis will be described a 37 ft. long sailboat manufacturing, a boat which is built as performance racing boat with modern and minimal cruising function. This cruiser/racer type of boat allows the owners to have some serious racing and option to use the yacht as a daily cruiser. This functionality is essential on the yachting sector because the technology improvement and researches allowing to make faster racing boats. The same technology will appear one day on performance or even in the cruising sector with some modification. It is a typical new trend in naval design, where high-performance racing boats and lux cruiser boats have similar hull lines and shape, but with different equipment. That is something that attracts customers to have good performance boat with different equipment as they preference and what will be purpose of the boat. The similar approach could be seen in the automobile industry, where technology, what has been used on racing cars, will be adopted on street-legal supercars. For that kind of universal boat have a high demand in the market for different consumer groups. Meanwhile, the boat is self will be able to keep the price for years. The more updated the boat can be, the higher will be the price of the boat on the second-hand market, and the bigger is the change that boat EOL will be postponed to beyond the future.

For pleasure craft production, there are several ways to produce boats. Usually, boatyards choose a solution, which is most economically effective and trying to use conventional methods as possible and focusing more on mass production. Therefore, product development is mostly related to cost efficiency. Unfortunately, technology-based development is more related to the push method than the pull method. The raw material producers and naval engineers, has been leading the process to introduce eco-friendly materials and sustainable production methods. From the market point of view, the demand is not so high, but it seems it is going to be changed, due global green way of thinking; it is because of the customer will pay more attention to reduce the footprint and meanwhile enjoying the joys of life.

For the previous reasons, this thesis will focus on 37 ft. yacht production and improvement for more eco-friendly, that after the boat has reached at the EOL for the dismantling, the impact on the environment would be as small as possible. Also, to evaluate how does it affect the total cost of the boat and market competitiveness. As input data will be, use the materials from 2014 and 2015, when the prototype was designed and built. The boat is designed by Cossutti yacht design and made in Estonia by Ridas Yacht & Composites. The boat was designed and build as a one-off racing boat to race under the ORC rating system. The deck is designed to be as ergonomic and similar to the full racing boat as possible, with large cockpit where can be move easily, low profile coach roof to be aerodynamic.

Meanwhile, interiors are ergonomic and comfortable, which suits for cruising. In structurally the boat is built to have the stiff as possible, the hull has been laminated with unidirectional fibre fabrics. In lamination, the scheme has been used three different types of core material: solid, foam and plywood, which has been used on the different areas of the boat. All the bulkheads are made from a composite sandwich or plywood, and they are laminated to the hull and deck. All the interiors are structural parts and are combine as a structure furniture.

Keywords: Sailing yacht production, sustainability, eco-friendly, recyclability and renewable materials.

1.1 Boatbuilding background

Since 1940 boat building has done serious changed in materials. Fibreglass as glass-reinforced plastic (GRP) was introduced in the 1930s. First glass fibre were discovered in 1932 and then 1936 first polyester resin (Marsh, 2006). Fibreglass was offering the continuous monocoque structures, what makes boats strong and watertight, along with ease of building the whole series to make identical boats. Ray Greene was first, who was able to produce a fibreglass small sailing dinghy in 1942, other 'plastic' boats followed appearing at a US boat show in 1947. The first fibreglass yacht was probably the Arion, a 42 ft. Herreshoff designed ketch, which was built in 1951 (Marsh, 2006). GRPs has particularly remained the same focus, many companies still use open moulds by traditional manual wet lay-up technique, like in old days. It requires no big investment for starting, which make it low entry-level technology accessibility for producing annually thousands of small working and leisure crafts. Those last six decades, the marine industry has been turning out increasing numbers of reinforced plastic leisure and working vessels. The International Council of Marine Industry Associations (ICOMIA) has estimated that there are more than 6 million leisure crafts in Europe (Marsh, End-of-life boat disposal – a looming issue, 2013).

Strangely that most of the fibreglass boats that have ever built are somehow survived until nowadays, probably it owes something to the fact that early boats were over-engineered (Marsh, 2006). Besides, where can be admit that composite vessel is highly durable, so the end-of-life disposal has not so far been a significant issue in society. In the 1960s, the marine industry became the largest market for reinforced plastics, though it would later be eclipsed by automotive use. Glass/polyester was and remained the primary material for marine constructors (Marsh, End-of-life boat disposal – a looming issue, 2013). GRP offers durability, workability and low cost. It has good resistance to corrosion, UV and seawater. Additionally having the advantages of strength and weight ratio, compared to conventional materials such as aluminium, steel and wood, which make boats lighter and faster.

After that, vinyl ester and epoxy resins were introduced, also other materials, like Kevlar, which has high resistance to great shock and impact loads (Marsh, End-of-life boat disposal – a looming issue, 2013). Later on, there were introduced carbon fibre, first in small racing dinghies began to benefit, then performance yachts. Away from craft shells and decks, the carbon was used for masts, spars, keel profiles (foils), rudders and other marine items, which need to be light and robust. In smaller craft industry building, boats of max. 50 m of length overall, composite materials is unrivalled with a share of 70% (Neşer, 2017).

There is three central technology in boat production, which mainly differs from the primary use of the material of the hull:

- Wood,
- Metal (steel and aluminium),
- Fibre-reinforced plastic (carbon fibre, glass fibre and Kevlar/aramid fibre)

Wood is the traditional material in boat building and spar construction, mainly because it is buoyant and relatively easy to handle, it is proved by the fact that has been used for hundreds of years. A wood boat is more demanding and requires much maintenance comparing boats, which are made of metal or fibre-reinforced plastic. The abrasion resistance is varied according to the wood density and hardness. Keel frames, mother wood or main bulkheads are traditionally made of hardwoods, like as oak. For planking will be using softer wood, like pine, cedar or larch.

There are known two types of wood construction, carvel and clinker. First one is moth hull form, where planks are joined edge by the edge and planks are attached to a frame. The second technology is Clinker, which is known in Scandinavia and Viking ages. The wooden planks are fixed to each other with a small overlap and connected with, nails, screws or glue.

Wood has the least environmental impact of all materials, what use in the marine industry. It is good because that is renewable resource and it is one of the first building materials in boating back in times. Different materials will not be compared by waste management, but also how much carbon dioxide will be realized to atmospheric during the process of growth of trees. In the Table 1.1 are described the carbon emission by material, it seems evident that wood is far the best through these indicators. Wood is low energy material, a net carbon negative footprint and a renewable resource, and it gives credence to need for greater attention to its use in the maritime sector (Bose & Vijith, 2012).

Table 1.1 Net carbon emissions in producing 01 ton of material (Bose & Vijith, 2012)

Material	Net carbon emissions (kg C/metric)	Net Carbon emissions including Carbon storage within the material (kg C/ metric ton)2
Framing Lumber	33	-457
Steel	694	694
Aluminium	4532	4532
Plastics	2502	2502

Metal boats are made of steel or aluminium. Steel is more common to the big ships, it is strong but heavy, about 30% heavier than aluminium. Steal is a very cheap material and has a relatively good thickness-strength ratio, for this reason, it is used in shipbuilding. On the other hand, the aluminium manufacturing techniques are complicated and requires higher construction skills, so it makes difficult to handle by amateur boat builders, besides it is costly. However, which is interesting, the aluminium from Bauxite ore is with high carbon emissions product and energy-intensive process. Producing aluminium from raw material is time-consuming and with many processes and steps. Aluminium is a light material, even comparing the GRP solid laminate. Fibreglass might have the advantage in weight for smaller boats where more curves and asymmetrical hull shape are, but for building large boats, with long and straight freeboards, the aluminium could be 15% lighter than polyester boats. In the small boat section, aluminium is popular in simple powerboats and fishing boats section because aluminium is more durable and requires little maintenance comparing the GRP boats. Ground with aluminium boats is less damaging than GRP boats, which will crack. Meanwhile, aluminium will deform and bend. Aluminium is one of a perfect material for recyclability since the secondary metal is recovered using only 3% of the energy consumed in the production of virgin metal by electrochemical purification (Gramann, Krapp, & Bertram, 2009). Even though aluminium ore is found in abundance, it is nonetheless a non-renewable resource (Jansen, Mayer, Roeder, & Wittamore, 2009). In Estonia, there are some aluminium crafts producers, the most know are Alunaut and Baltic Workboats. The last one is more focused on small ships, and working boats, but still they strong brand in the local community, more known than GRP boat production in Estonia.

The other advantage of aluminium is no need to create moulds, which is time-consuming to develop and build them. Aluminium is a design that is more robust with low surface roughness and has a low cost of the budget. Aluminium is regular material use as sailing spars since the 1960s, after it replaces the wooden spar items. Aluminium mast is a lightweight, high strength, easy to maintain, low cost comparing carbon, that price can be twice as high, the wooden mast that requires much handicraft.

Designers are increasingly changing to use composite materials in yacht design development, e.g. solving problems, improving performance and productivity, and innovating new products. There are many benefits associated with composite materials, such as (Adams, et al., 2015):

- high strength and stiffness that can be orientated to meet specific design requirements;
- low weight;
- design flexibility - can be formed into any shape;
- dimensional stability - yield point is the breaking point
- high dielectric strength - good electrical insulating properties;
- corrosion resistance - resin systems can provide long-term resistance to degradation;
- parts consolidation - mouldings can often replace assemblies;
- finishing - colour can be moulded in for long-lasting appearance;
- low tooling costs - can be lower than tooling and finishing costs for materials such as steel.

Fibre-reinforced plastic is a composite material made of a polymer matrix (resin) reinforced with fibres fabric. It is common to use from racing boast, which has to be light as possible, to cruising and leisure boat, which have been cheap and durable. America's Cup, Ocean, and Offshore racing boats are good examples where high-performance product today are built of fibre-reinforced plastic. One of the reasons why fibreglass is popular because it can be mould into all kind of shape and it can be applied easily to series production to be money's worth from the output of Fibre-reinforced plastic items. There are there types of common fibre-reinforced plastic uses in the boat building industry: carbon fibre, glass fibre, Kevlar/aramid fibre.

Table 1.2 Different materials (Kers & Veinthal, 2011)

Material	Density kg/m3	Tensile strength Rm, MPa	elastic modulus E, GPa
E-glass	2540	1500-2000	70
S-glass	2520	2600	86
Carbon	1740	4000-7000	230-300
Aramid (Kevlar)	1450	2700	130

Glass fibre is the most useable FRP in the yacht building industry. Approximately 90% of plastic boats are made of fibreglass. On the physical performance of fibreglass is lower than carbon fibre or Kevlar, but the material has still good performance comparing with other alternatives in boat building. The top advantage of glass fibre is the low cost, and the raw material is easy to handle, fabric is acceptable of using different resins and can bind with them. Glass fibre is available on the market with a different variation, with distinctive characteristic and price level, which give producers to use it in numerous sectors. Besides, in the yacht industry, the glass fibre is used in construction, pipes, tubes, automobiles and wind turbines. It has flexible features, it gives numerous options to producers, to use different fabrics and methods, to optimize manufacturing processes in their best ways.

Carbon fibre is material with low weight, high stiffness, high tensile strength, high-temperature tolerance and low thermal expansion. Carbon is expensive compared with similar fibres, such as glass fibres or Kevlar fibres. Usually, carbon fibre is used in top high-end performance sailing yachts and mainly because of the good strength-weight ratio. In the use of carbon there also difference in strength of the material. There are also high- modulus carbon, compared with the regular carbon the mast tube could be 10-20% lighter, depending on the producer the cost of the mast increase 30-40%, which makes the total price high. Carbon is a common raw material for mast production, which is expensive but is lighter than aluminium mast, up to 50% (in case comparing only the tube). Because adding fittings like headbox, spreaders and blocks, the spread on mast, the total weight difference would not be too big, if it has used steel and aluminium items, which is common in mast building. To achieve a weight advantage, it is required to use carbon in adding fittings and carbon standing rigging, otherwise, the total rig saving can be 10-20%. In the end carbon mast using, might raise the question cost-effectiveness and advantaged of weight saving.

Aramid (Kevlar) fibres are known of heat-resistant and robust synthetic fibres, which are commonly used in aerospace and military sectors, e.g. bulletproof vests. Aramid is the most widely used material for running and standing rig, due low creep what it provides is efficient for ropes and composite cables. The downside, Kevlar is not durable for UV resistance, the ultraviolet component of sunlight degrades and decomposes Kevlar, a problem called as UV degradation. Aramid fibres have a high elongation at break, which means high impact resistance compared with alternative reinforcing fibres, but still, it has higher cost comparing the glass fibre.

Material development and suitability have led to sandwich-type construction fibres. The previous FRPs are used as sandwich construction. The sandwich structure is made of three layers: a low-density core and a thin skin-layer bonded to each side. The low-density material is known as foam, lightweight wood and metal. Sandwich construction is typical in a yacht, automotive, space and plane industries to the lightness of panel.

Yacht building sustainability requires renewable materials or materials recycled from reused wastes, and also increasing demand for environmentally friendly materials and new natural fibres from biomaterials.

2. METHODOLOGY

2.1. Methods of composite boat building

The various materials (wood, metal or plastic), what determine the technology, but there are also several options to produces FRP boats in different ways. Before a company starts productions, it is crucial to identify opportunities and needs of the product. It is related to new product development processes.

Table 2. Moulds cost (Kers & Veinthal, 2011)

Method	Mould cost for average cost x 1000 euros	investments in equipment x 1000 euros
hand laminating	1-2	3-15
spray laminating	1-2	10-30
Prepreg vacuum bagging	1-2	10-30
Vacuum injection moulding	1-2	15-30

In yachting production, the key input is to understand what kind of boat type will be built and in what purposes, which technology is the most sensible to use. For that, there are several methods for laminations in Table 2.1. The most know is wet hand laminating, oldest and the simplest process for the manufacturing of fibre-reinforced plastics, where the material will be set on mould layer by layer and laminated by hand. This lamination has the best quality and price ratio, where tensile and strength will remain relatively high. If construction requires better quality in high-stress areas or thermal stability, then carbon and Kevlar are used instead of glass fibre. Those material needs to use epoxy resin, which has better mechanical properties than polyester resin, but also higher cost like fibres them self (Kers & Veinthal, 2011). Using the hand lamination method the wet fibre will be located to the mould, it is important to roll it airtight and avoid any bubbles that reduce the laminate strength. In increase, the quality can use the vacuum, with constant under pressure in the vacuum bag, and the laminate can be consolidated to the tight and solid.

The hand lamination is a low cost and low entry barrier, but is challenging to produce bigger items because it is time-consuming. The lamination takes more than one day, because there might be an issue with fibre fabric overlapping quality and a total weight of that because the lamination is done by sections day by day. The other issue with hand lamination is related to the fibre direction, nowadays, engineers try to calculate the stress level precisely as possible to make item light or reduce the raw material consumption. Especially, if using unidirectional fibre fabric, it is complicated to maintain fibre required direction because turning the hand lamination the direction of yarn can be changed and reduce the total strength.

Spray laminating is common in small powerboats or yachts category. Advantage of that is the low cost of production. Raw material quality is lower- both fibre and resin. Besides, the cycle time is fast. The fibre and resin are sprayed together to the mould and after will be rolled to airtight. All those matters will keep the boat price down. On the downside of that method is the fibre fabric is not directed and the required strength achieved by overwhelming, which makes boat heavy.

Prepreg vacuum bagging is a method where fibre fabric is pre-impregnated with activated resin by raw material supplier and it is delivered as rolls, where fibre is being between the film. The film will be removed, the special formulation of the epoxy start harden, at room temperature the curing process is slow and at freezing temperatures (around -20 °C) the process is suspended almost wholly. For that reason, the material is delivered in the containers, which has a cooling system. Prepreg curing starts around 60 degrees, but common in production to reach about 100 °C. This temperature can be reached by domestic and commercial cooking ovens. The solidness will be given by vacuum infusion. The high cooking temperatures in the curing process requires better moulds quality, which handles those temperatures. The standard polyester moulds are not suitable for prepreg fibre, it is common to use moulds that are made from high-temperature resin (epoxy or vinyl ester) or metal (stainless steel/aluminium). The prepreg vacuum bagging advantage that the direction of fibre fabric can be directed easily and does not require hand rolling, which can mix up fabric structure. For this reason, prepreg fabric is favourite in high-end products, in racing boats and racing cars, where every gram will matter in performance because labour workers can follow engineers' instruction of lamination scheme without overwhelming. On the negative side, there is a large amount of consumable waste material at the end of the moulding process (e.g. polythene bagging material, flow mesh, bleeder layer and peel ply) (Jansen, Mayer, Roeder, & Wittamore, 2009).

Vacuum injection moulding is a method where the resin will be led to the mould by using under pressure and trying to do it as efficient as possible (Kers & Veinthal, 2011). This process offers the benefit of not requiring an expensive autoclave while also being capable of producing large parts that method is widespread in the industry can be use sandwich panels. The structure made of three layers: a low-density core material, and thin skin-layers on cover material, the increasing the overall thickness of the panel, which often improves the structural attributes. The further afield are the surface elements are from the neutralizer as core body, the greater is the inflexibility (Kers & Veinthal, 2011). Sandwich panels are used in the construction where a combination of high structural stiffness and low weight is required.

Along with the solid lamination, the yacht industry is one of those where is common to use a sandwich panel, via that increase the boat stiffness and reduce the total weight. Vacuum injection moulding allows producing high-quality sandwich panels, where fibre fabric can easily direct in the wanted direction. Therefore, with some thickness of core material and thin skin of fibre can be produced light and stiff sandwich panel.

Typically, in vacuum injection moulding, uses a low viscosity polyester or vinyl ester resin along with fibres, it ensures that resin can seep all around the mould and prevent try parts on items. In high-quality composite parts air bubbles must be avoided because if the resin flows through the mould improperly, it also leads to the formation of air bubbles and uncured fibre. Have side effects, the incorrectly made process can cause a violation of the whole product, it means that trained employees are required.

Comparing those four methods, the cost of the mould is the same, and there are not much difference from the mould itself. Only in prepreg vacuum bagging, in this case for the cooking process the resin which is used in the mould itself, have to handle high temperatures. The differences are the investments into equipment, but not so much as the total cost, but what kind of product will be produced and how big is item. Each of them has advantage and disadvantage. From the point of view, the results of the environmental impact of vacuum infusion method are much higher than hand lay-up method due to its higher energy consumption (Önal & Neşer, 2018).

2.2 Recycle EOL

Today the marine composite industry is faced with two major issues: first, the need to recycle end-of-life-vessels in a way, that has not a negative impact on the environment, and secondly, finding a way of designing new boats that will not leave future generations in the same predicament, which calls as "sustainability" (Önal & Neşer, 2018).

Although GRP provides designers, engineers and producers a product with moderate quality and long life span, its poor recyclability of that thermoset plastic has always been a problematic area mainly due to its inherent heterogeneous structure (Neşer, 2017). Because of that, the marine composite industry is faced with that two-important problems. The waste management and environmental legislation should require all engineering materials to be properly recovered and recycled at end-of-life, like products in automobiles industry. However, unfortunately, the national legislation is different between the countries, that some counties do not have a specification to handle the end-of-life vessel. A boat has reached at EOL cycle, its economic value is meagre and when its renovation is not economically competitive. There are several choices for the owner dealing with an EOL boat, these are: refurbishing, selling, recycling or abandoning (Serranti, Capobianco, Bonifazi, & Donne, 2016)

There is a growing trend of vessels that are abandoned in marinas, at sea (sunk) or even in fields by their last owners who faced with high costs and non-working waste management infrastructure. Usually, the all signs that could help identify those owners are removed before abandonment, e.g. hull identification number (builders' numbers), sail numbers, registration details, which means that marinas and local authorities have to deal with them. The number of abandoned boats at marinas is increasing, and in some marinas, abandoned boats already represent 2-3% of their total capacity (Önal & Neşer, 2018).

A well-known case in a sailing community is from at the end of the 2000s and being of 2010s. After the 2007 Louis Vuitton Cup, which is the pre-event for one of the worlds the most prestigious sports event, America's cup, the Spanish team Desafío Español's, abandon the boat after the races and program was over (Figure 2.1.). The boat was left at the yacht club, docked for years after her keel fell off, which was causing the mast breaking. This extreme example abandoning the yacht, which might cost multi-million euros, but this shows the irresponsibility of carbon or FRP recycle management. Boating is a hobby, leisure, where attitudes can be changed over time, so that people have lack of time to boating, not taking care of boats, or there can be an economic recession (affect owners budget), from that point the boat starts to a fall apart. That might be a first trigger for the ghost ship at the marina, where one point might be the boat value is lower than recycling cost. Therefore, the cost of the scarping will be the issue. There has been some studies, e.g. in France were concluded that decommissioning would cost around € 530 for a 4 m long craft and € 4,750 for 12 m long. Also, Finnish Boat Recycling Project (Finnboat) found that tonne of boat weight cost ca € 150, plus transport services/ logistics at some € 70 per hour. Some other researchers have found the average cost of dismantling a 7 m long boat, including logistics is around € 800, rising to approximately € 1500 for a 10-12 m craft and € 15,000 for a 15 m vessel (Marsh, End-of-life boat disposal – a looming issue, 2013). Generally, the boat might be the same lousy investment as a car, and it would not hold the price, even more, it requires extra payments for maintenances. The main issue is comparable with scraping cars on society, when a vehicle has reached EOL, but has left on the streets. Because of the low value and properly scarping the vehicles is a resource-intensive activity.

Figure 2.1. Abounded yacht (Sailing Anarchy, 2014)

In the case were boat has abounded, the first issue is not the GRP recycle. Because there are other items which needs to remove first, like oils and fuels, bilge water, batteries (usually lead batteries) and other pollutants, which can leak easily to environment.

Along GRP production items came up a problem, what to do with wastes or items which has reached to the end of their life. Comparing metal and wooden boats, which are made of recyclable or naturally material decomposing, the process would be much more complicated. If you take a close look at a sailboat production from really begin and reaching to the EOL, you can consider that GRP waste is not only an issue at EOL, but also the production will start because some of the items will arrive at EOL in production process, Figure 2.2. The manufacturing start from the plug production, which is 1:1 copy of the boat, usually, it is made of MFD or ESP form and covered with fibreglass after use it is a waste and will be thrown away. Making a mould and after manufacturing the GRP hull generate a sufficient amount of wastes, which causes the same problem as the boat itself, when it reaches to the EOL. The GRP wastes management issue is not only related to owners and their yachts, but it also involves the boat builders, who could be the beacons in that topic. Anil N. Netravali, who has been researching alternative 'fully green' composites for nearly 20 years at Cornell University, has found that until today do not have an "environment-friendly" solution for GRP recycling (Sealy C. , 2019). The reducing energy use and waste via applying to recycle and lowering emissions, the sustainable engineering can be called "good engineering" (Önal & Neşer, 2018). The composites can be considered as eco-friendly when the polymer matrix is biodegradable (e.g., if filled with natural-organic fillers), but also when it comes from renewable sources (Fragassa, 2017). Leaving GRP as landfill is not eco-friendly and sustainable in a longer period. It is something that GRP items producer's clients think, it matters and is requiring companies to deal with that.

Meanwhile, the world is going through a low carbon revolution, and for this reason, composite is potential to reduce greenhouse gas emissions via lightness and robustness of the material, in this GRP is good for that. In this case, the sailing is the most efficient way to reduce the emission and afloat with the wind. Meanwhile choosing the light performance yacht, the wind can be used the most efficient way. On the other hand, the difficulty of recycling (GRP) is struggling in construction and automotive, where the recycle pressure is the highest, has put engineers under pressure to look for options to recycle and reuse the FRP materials. It is essential to understand that the reduction of environmental impact can be made in every single phase of the entire lifetime of the boats. With this approach, it is possible to intervene on a single phase and improve it and to be able to establish new strategies that will enable designers to take effective action for the design and the construction of new generation boats with higher performance and lower environmental impact (Cucinotta, Guglielmino, & Sfravara, 2017).

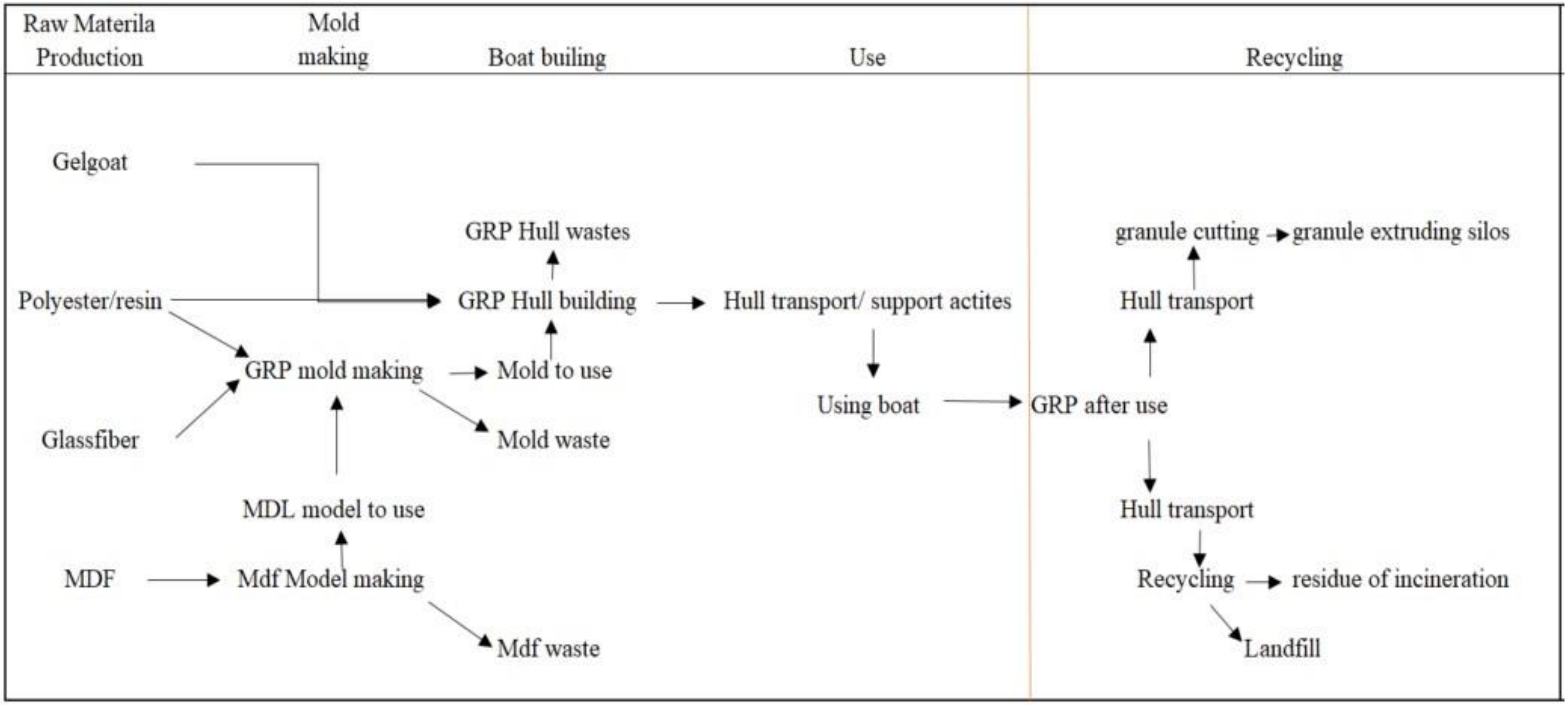


Figure 2. The life cycle of a GRP boat hull (Önal & Neşer, 2018).

In FRP and GRP recycling technologies are divided in three categories:

- thermal;
- mechanical;
- chemical.

The technological and economic restrictions are the reasons why incineration is popular in GRP recycling for energy recovery and with little or nothing recovery of fibre fabrics. Unlike materials such as steel and aluminium that have scrap value after the boat has reached to end of life, companies do not see an economic return from recycling composites. Incineration of GRP is not practical since about 50-70% of the material is mineral and would be left as ash, which still needs to be landfilled. Also, the leftovers, the calcium carbonate is not so valuable and it is not economical compared to landfilling, where a landfill is still an option. Some of the countries have been disabled the landfilling of reinforced composite materials, there will be burning organic resin providing energy and from minerals will be provided feedstock for the cement clinker (Job, 2013).

A chemical process, calling pyrolysis, the organic resin matrix is decomposed in an inert atmosphere and high temperature, reaction products can be used as fuels or ingredients for other petrochemical-based materials. The process is operating at temperatures between 450 and 650 °C, has developed for separating the fibres from the resin (Adams, et al., 2015). The strength of the recovered fibres was reduced by 50%, and the process leaves the fibres randomly orientated, which decrease their usefulness (Feraboli, et al., 2012). Pyrolysis is much less cost-effective than grinding or crushing (Adams, et al., 2015).
There are also other chemical processes, calling hydrolysis involves depolymerisation of the resin matrix using water and an acid or base catalyst. This process can only be used with limited matrixes on FRPs, e.g. polyester. The problems with hydrolysis are that the scrap material has to be separated into matrix polymer types before recycling and also post-processing is needed to recover the fibres fabric. (Adams, et al., 2015)

The scraping of GRP `s via mechanical grinding has already existed in the '70s. The mechanical recycling based on shredding and grinding and after separation, fibre-rich and resin-rich fraction from each other. It can be applied to any components made from thermosetting FRP from cheap glass-reinforced plastic products to expensive carbon fibre reinforced plastic The bulk parts are broken into 50-200 mm pieces, which are crushed or ground into different grades using a hammer mill or similar device (Adams, et al., 2015). The finest powder grades are used as fillers (Henshaw, Han, & Owens, 1996). The recycled material is low cost-effective because at the being it is energy-intensive and the recycled material have a low quality (Neşer, 2017). The grinded and reused GRP as a filler or reinforcement in a resin matrix is stiffer, but the strength is much lower than that of the virgin material, also flexural strength will decrease (Adams, et al., 2015). The recycling via grinding requires a significant amount of energy to be the finest as possible, to use as filler (Job, 2013). The easiest way of recycling is a thermoset plastic, in terms of technological level and initial cost (Neşer, 2017). One of the reasons why grinding is not cost-effective, the leftover calcium carbonate can be reuse, but not reused material can be purchased at meagre cost (Job, 2013). In a comparison of the three recycling techniques, the mechanical way of recycling (granule extruding) shows better environmental impacts except for terrestrial toxicity, photochemical oxidation and acidification. The alternatives, as landfill has the highest ecological impacts except 'global warming potential' and 'human toxicity, which are the highest (Önal & Neşer, 2018).

Composites have a high thermal energy content, despite the existence of inorganic reinforcements. In Carbon fibre reinforced plastics (CFRPs), there is a recycling process, where fibre recovery followed by recovered fibre use in a new item. In this case, end-of-life composite materials are shredded and then heated to high temperatures to burn out the polymer component (Sealy, 2019). Furthermore, most conventional polymers (resin and vinyl ester) are made from petroleum, which is known as a limited source on planet earth.

The limitation of such recycling approaches is that the resulting fibres are short and form a jumbled mass, very different from the long aligned unidirectional fibres, what is required for high-performance composites (Sealy, 2019). The high-grade carbon fibre prepreg is the most challenging fibre to recycle. It lost the most advantage of original material properties (Adams, et al., 2015). There are other sophisticated options, which are more effective to produce a higher quality of recycled material than just utilize resin more productively than simply as a fuel to burn – through even the resin is not without value. Still maintaining the mechanical properties of plastic through the recycling processes is a crucial challenge in developing a commercial recovery process at all, at the moment the trade-offs exist between the competing recycling technologies (Sealy, 2019). In the UK there is a company called ELG Carbon Fibre, they work with INEOS Team UK, a British America's Cup sailing team. The ELG's recycled carbon fibre is in the team's America's Cup boat, a 75 ft monohull with foils and a soft wing mainsail, the boat will sail 2021 America's Cup. The recovered fibres are converted into milled and chopped products to make thermoset and thermoplastic compounds and nonwoven mats (Nickels, 2019). The precise list of items, what used on the boat, have not been revealed, but there is know that recycled non-woven materials is used in the cradles (frame which support the vessel during transit), also as the hull and deck moulds. However, this is a small amount of recycling material comparing the details list of the boat. In huge budget sailing teams, seems the recycling would not be an issue to produce secondary or supporting parts, but there are not known many cases for high performance recycle carbon use on a boat.

2.2. Green polymers

A German yacht builder introduced in 2015 series of a boat, what called greenbente24, which was built from 80% renewable materials like flax, cork and bio-based epoxy resin. It has the same weight and stiffness as a standard boat (bente24), but the production of the biocomposite boat saves 80% energy throughout the production process when compared to the traditional materials. The company were founded in 2015, when its first yacht, the Bente 24 got much attention and more than 120 were built, but company high development and manufacturing costs is lead to bankrupt (Stickland, 2020). Unfortunately, for today Bente yachts is bankrupted. This excellent example of how difficult to produce cost-effectively small boats, it can be imagen what kind of effort requires the development and launch the vessel, which is made of 100% recycled or renewable materials.

Currently, polymer composites that are used in production are based on petrochemical sources, but there are other options for sustainable polymers and the renewable resource. Biocomposites contain wood or other natural fibres, and a polymer as a matrix, in Figure 2.3. (Partanen & Carus, 2019). The automotive industry has investigated bio-composites based natural organic materials, e.g. cellulose, sisal, jute, ta, as alternatives to classical glass or carbon fibre composites (Gramann, Krapp, & Bertram, 2009). Technological fibres such as glass, carbon and aramid are widely known yacht and boat industries, but there should be more focus on sustainable materials, such as flax, hemp, and cotton (Fragassa, 2017). The natural biodegradable polymer composites is a relevant topic in renewable sources implementation in the yacht industry. Plant fibres such as cotton, flax, hemp, jute or nettle are mostly made of cellulose and animal origin fibres are made of protein (hair, silk, wool). Biopolymers are mainly classified as agro polymers (starch, cellulose) and biodegradable polyesters (obtained by microbiological production). The price difference between bioplastics and synthetic plastics is expected to be narrow, because of continued breakthroughs in production and processing technology, furthers increases in base crude oil, close substitute energy prices and government regulations to favouring greater use of renewable energy and waste materials (Neşer, 2017). Biodegradable polymer are less fire-resistant, and their quality might be more variable, the price may change according to the yield of crop and moisture can cause fibres to swell, which makes yacht builders insecure about product durability (Gramann, Krapp, & Bertram, 2009). The poor wettability and incompatibility with some polymeric matrices (Taj, Munawar, & Khan, 2007) are side effects that could make the raw materials using in production processes more complicated. Most of plastics by themselves are complicated to use for high-load applications due to their lack of sufficient strength, stiffness, and dimensional stability, and even the fibres possess high strength and stiffness can be difficult to use in load-bearing applications because of their multi fibrous structure. At the beginning of the life cycle, the composites based on natural fibres have a lightweight, high strength to weight ratio and good stiffness (Neşer, 2017). Nevertheless significant problems with the use of natural fibres in composites is their high moisture sensitivity, which is leading to severe reduction of mechanical properties and delamination. The reduction in fibres mechanical properties causes by the poor interfacial bonding between resin matrices and fibres. Therefore, the fibre surface of render is not hydrophobic and also poor compatible with resin matrices. Most producers still use fossil-based polymers for the production of composites, meanwhile there are a lot of bio-based polymers on the market to produce partly or fully bio-based composites (Taj, Munawar, & Khan, 2007). In general, the lower impact of bio-composite products comes from two reasons; first, the production of the natural fibre is less energy consuming compared to glass fibre. Secondly, the product in incineration processes at the EOL, burning of natural fibres will include recovered energy and lower carbon dioxide, while glass burning is difficult, expensive, and physically and environmentally dangerous (Castegnaro, et al., 2017).

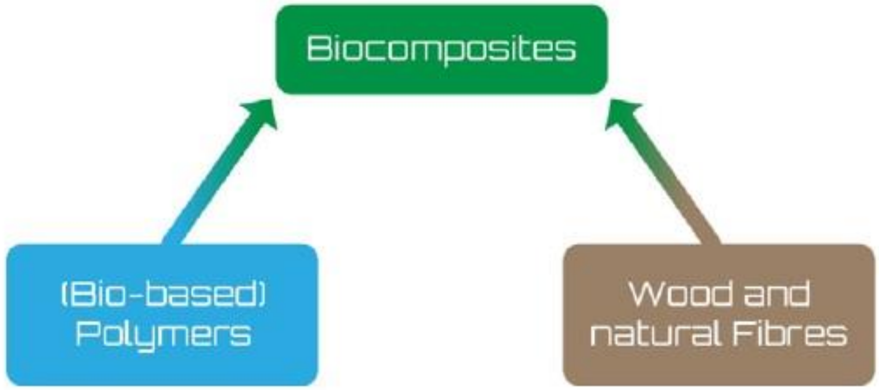


Figure 2.3. Biocomposites contain wood or other natural fibres and a polymer as a matrix. (Partanen & Carus, 2019)

Table 2.2 are described several the mechanical properties of natural fibres comparison with carbon, glass and Kevlar fibre. Some of the fabric are known and has been used for thousands of years, e.g. hemp, flax. The flax is one of the oldest textiles, back in the Mesopotamian times. Flax is growing in Europe, USA, China and India, which mean it is presented in larger economic premises. It grows fast, from seed to crop takes eight weeks, really needs irrigation and chemicals are also not required. The fibre is sound, but also flexible, and it is particularly inextensible fibre, stretches slightly with an increase of tension. Flax fibre loses strength gradually on exposure to sunlight. It is expensive fibre, because of the many labour-intensive production stages, but is it still used as high value-added reinforcement items, where are only medium stress range exposed (Mohanty, Misra, & Drzal, 2005). Flax is an attractive natural fibre reinforcement because it is easy to handle, has good mechanical properties, good change bonding with polymer matrices, and high aspect ratios (Chai, Bickerton, Bhattacharyya, & Das, 2012). The downside of the flex, as another natural fibre is, it is difficult to use hand lay-up, because the natural material can absorb much resin without compression, for this reason, the vacuum injection is needed. Automotive and building industries are increasing the utilization of flax fibres day by day due to cost-saving and the green movement (Taj, Munawar, & Khan, 2007).

The other well knows natural fibre is hemp and cultivates more than 12000 years. Industrial hemp has been used for years making ropes, but nowadays, fibre is used to make clothes, textiles, toys, shoes or even fuel. The natural fibres are fully biodegradable, non-toxic and may be recycled (Taj, Munawar, & Khan, 2007). Hemp has good moisture resistance and rots slowly, the tenacity is approximately 20% higher than flax, but elongation is low at break (Mohanty, Misra, & Drzal, 2005).

Table 2.2 Properties of natural fibres (Neşer, 2017) (Fragassa, 2017) (Zivkovic, Fragassa, Pavlovic, & Brugo, 2017)

Material	Density (g/cm^3)	Tensile strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)
Spiker silk	1,3	1300-2000	30	28-30
Flax	1,45	500-900	50-70	1,5-4,0
Hemp	1,48	350-800	30-60	1,6-4,0
Kenaf	1,3	400-700	25-50	1,7-2,1
Jute	1,3	300-700	20-50	1,2-3,0
Bamboo	1,4	500-740	30-50	2
Sizal	1,5	300-500	10-30	2,5
Coconut	1,2	150-180	4-6	20-40
Fibreglass	2,5	1200-1800	72	2,5-4
Carbon fibre	1,4	4000	235	2
Kevlar	1,44	3600-4100	130	2,2-4,4
Basalt fibre	2,67	2800-3100	87	3,15

Meanwhile the flax and hemp, which are both quite common in Europe market and they are also produced in Europe, which simplifies the supply chain. The Jute fibre is another essential plant fibre, similar to cotton. It is native from Mediterranean and spreader to far, today Ganges River and Bramhaputra River deltas are known for Jute production. Fibre is not UV resistant and starts to lose tensile strength under the sun, and it has little resistance to moisture (Mohanty, Misra, & Drzal, 2005). Disadvantage of the jute fibres are high water absorption and the countries where jute is produced (e.g., Bangladesh), it will set a limit for European yacht production (Castegnaro, et al., 2017). The tensile strength of jute is lower compared with hemp or flex. However, it is still good raw-material to produce low-cost fishing boats, and there has been reviewed and studied jute fibre-reinforced thermoset with jute/epoxy and jute/polyester, which showed decent results' (Mohanty, Misra, & Drzal, 2005).

The Basalt fibre is a material, which is made from extremely fine fibres of basalt and has produced a hard volcanic rock. It has better mechanical properties than fibreglass, but being significantly cheaper than carbon fibre, meanwhile, it is a material with a low ecological footprint, good heat performance and outstanding chemical resistance. Basalt fibre is produced in a similar process in many aspects as used to make glass fibres. Since there is no boron or any other alkali metal oxide generated in melting down the basalt, the production process of basalt fibre does not create any pollutant, which makes it a new environment-friendly fibre in the 21st century. Basalt has been used on boats, e.g. produced by the sun-bird company the results it has shown that most of the properties are better than the traditional fibreglass boats (Zhang, Tang, Pu, & Zhang, 2011). Basalt fibre has low water absorption, which is vital in the yacht building sector. As other natural fibre, the basalt fibre manufacturers have less direct control over the purity and consistency of the raw basalt stone. It puts manufacturers to choose or prefer to use material from a single supplier to avoid the uncontrollable variables in basalt fabric. In chopped mat, roving and unidirectional fabric forms, basalt fibres exhibit a higher breaking load and higher Young's modulus than E-glass (Ross, 2006). Basalt fibres are naturally resistant to ultraviolet (UV), which is good of sailing point of view.

The Natural fibres can be derived from leaves (e.g., sisal), bast (e.g., flax, hemp) and seeds (e.g., cotton) (Fragassa, 2017). According to the studies, the tensile strength of natural fibres such as hemp, flax, jute, and sisal are lower than the tensile strength of glass fibre. The density of glass fibres is much higher, about double the density of most of the natural fibres. Thus, the specific strength of some of the natural fibres are quite comparable to glass fibres (Mohanty, Misra, & Drzal, 2002). The young's modulus is slightly higher on fibreglass than natural fibres, which make them similar. However, essential advantages in terms of specific material properties, the natural fibres comparing synthetic ones, fibre fabric can weight up to 40% less, and it is possible to improve flexural strength, stiffness and flexibility.

3. RESEARCH

3.1. Over-view of the objective

The objective of that master thesis is boat is 37 ft. racing boat, pictured in Figure 3.1 The boat was designed and build as a one-off racing boat to race under the ORC rating system. It is designed by Maurizio Cossuti and built by Ridas Yacht & Composites in Estonia. Designing and building process started in 2014 fall and boat launched in 2015 July. From scratch to launch, it took approximately ten months.

Figure 3.1. *A 37-ft yacht, photo by Andre Carloni*

The yacht has made from e-glass with vacuum infusion technology. The deck has designed to be as ergonomic and similar to the full racing boat as possible, with large cockpit where can be move easily, low profile coach roof to be aerodynamic. Meanwhile, interiors are ergonomic and comfortable, which suits for cruising. In structurally the boat is built to have the stiffness as possible, the hull has laminated unidirectional and bidirectional e-glass fibre fabrics. In layup schema, there has used three different types of core materials: solid, foam and plywood, which has been used on the different areas of the boat. All the bulkheads are made with a composite sandwich or marine plywood, and they are laminated to the hull and deck. All the interiors are structural parts and are combine the structure with furniture.

3.2. Preparation and process selection

In the sailboat manufacturing industry the one of the critical matter is to choose material and process for production, which is based on craft (prototype, one-off) or serial production method. As a point of view the environmental friendliness, waste management begins from there, when choosing process. This determines is the plug favourable to use as once or the mould will be more cost-efficient. Building on the plug will be more beneficial if one boat is built because it is more cost-effective (no need for mould), but meanwhile, the boat outer surface requires more processing in the end, e.g. adding much filler. Besides, the boat surface quality would not be good and lasting as mould produced hull. A plug is only available to use once, and it would not be built for last. In the serial production is common to use the mould, which is taken from the plug. What makes the mould expensive are the working hours or CNC machining, before getting the mould, must build a plug, which is a copy of final boat and from that plug, it is possible to make a mould. For producing the same technology there were used on 37 ft. a yacht, first plug and then mould. It was caused by the idea, in the futures to have the option to make replicates to sell more boats and using mould can be labour working cost to reduce.

First was built deck plug on Figure 3.2, which is a copy of the deck. The plug is for one single-use, which becomes trash after use and must be handle as a waste. The plug consists of mainly the medium-density fibreboard (MDF), which is wood-based material made from lignocellulosic fibres, what is bonded together by synthetic resin under heat and pressure. MDF can be considered green and environmentally friendly because it is manufactured from a combination of real wood approx. 80% and recyclable products, which breaking down bits of wood into wood fibres, then pressured and stuck together with resin and wax. MDF fibres contained approximately 10% cured urea-formaldehyde resin and 1% wax water repellent. This what makes it toxic and not recyclable. Now there is no commercially accepted method to recycle MDF, so it is burned, and ashes will be landfilled. Current MDF what is used in Europe has lower amounts of formaldehyde, than it was before and called low formaldehyde MDF. The same low formaldehyde MDF that is produced in Poland by Kronopol Sp. z.o.o, has been used for making this 37 ft. yacht deck plug. On the market, there are alternative for more eco friendly MDFs, the ECOBoard are agri-fibre panels, which use a special No Added Formaldehyde (NAF) resin, that seems good alternative material. It is designed, that only 3% of resin is needed for bonding (ecoboardinternational, 2020). The MDF boards will be used as longitudinal and transverse bulkheads of the plug. The First layer is spruce or pine boards and covered with thin fibreboards, after that the deck plug surface will be processed to smooth as possible and later will be painted. After that, the plug is ready for moulding.

Figure 3.2. 37 ft. yacht deck plug

In that case are used female deck mould, because outer parts dimensions are more important than its inner dimensions. Mould consists of the glass fibre and supportive metal frame. The used glass fibre was chopped strand mat (CSM), which are the most widely used of all composite reinforcement materials in the boat industry. CMS consist of short strands of glass is randomly distributed and bound to create a mat which can then be wetted with resin and used as a general-purpose reinforcement for traditional fibreglass moulds or parts. Due the relatively low performance compared with alternative reinforcements, like carbon fibre, aramid, the chopped strand mat is certainly not at the most advanced composites material, but there are still items and applications where it is used in cheap parts. It is also used widely in the production of patterns and moulds for more advanced composites. For producing mould for 37.ft yacht the glass fibre, CSM 450 g/m^2, the alternative can be used basalt fibre cover mats. The compatibility is excellent between the binder of basalt fibre surface mat and resin, which can improve the formability of different composites. Basalt is used even at America's Cup, in the next edition 2021 has limited construction methods, that the moulds have to be constructed from fibres with low embodied energy (e.g. basalt) (Royal New Zealand Yacht Squadron and Circolo Della Vela Sicilia, 2018).

For mould making, are used the hand lay-up, but as are know that hand lay-up is challenging to use because the material can absorb much resin without compression. In that 37 ft. production, it is not crucial that the weight of the mould via higher resin consumption, the more important is to have a strong and solid lamination. Currently, there has been used PVC 20mm foam inside the mould for increasing the strength, but it can be replaced by the balsa core, which would be much more eco-friendly. The metal frame for supporting will be the same.

Figure 3.3. 37 ft. yacht deck mould

The hull preparation will be the same; first is produced the plug and then the mould. In this case, the plug was produced with CNC machine in Figure 3.4. Using the CNC machine saves time, and quality is better by the cost is meanwhile higher. The plug was machined out from EPS from, but reducing the foam consumption and deliverability, first were built a wooden frame, which was covered with foam blocks, which will be machined out. The plug was covered with glass fibre CSM 450 g/m^2, and again for the excellent alternative, it can be replaced by basalt mats after that the surface will be painted and finished. Making the mould process will the same as it was in the deck. Basalt fibre surface mat 100 g/m^2 would be the outer and inner skin, while with the balsa core material adds thinness and strength to it.

Figure 3.4 CNC machined plug, covered with GRP

In Table 3.1 are described the current layup of moulds and alternative solutions. The outer skins will be made of basalt fibre surface mat 100 g/m^2, as core material balsa Baltex SBC, which is an ecological product and are 100% plantation grown. Besides, it has required FSC-certification. FSC is Forest Stewardship Council certification, which is approved forests all over the world to ensure they meet the highest environmental and social standards. As a resin will be use ONE High Biobased Laminating Epoxy. High biobased epoxy system designed for composites, coating, and adhesive applications. Bio-based Epoxy resin is produced of 30% from carbon plant origin and has a lower environmental impact than standard epoxy resins.

For increasing the strength, more layers are required, and more layer, it means more resin consumption, which in the end affect the total cost of the moulds. Usually, the moulds are overwhelmed of strength for a reason, they would last longer and would not deform over time, which affect the shape of final product.

Table 3.1 Moulds layup

Deck and Hull Mould layup							**Total surface = 99 m²**	
	Layer	**Material**	**Reinforce. Weight** [g/m²]	**N° of layers**	**Lam. weight unit.** [kg/m²]	**Lam. area** [m²]	**Lam. Weight tot.** kg	**Resin** kg
Outer Skin	Current	E-CSM 450gm	450	5	1,50	514,5	771,7	540,2
	Alternative	Basalt fibre surface mat	100	20	0,33	2079,0	686,0	485,1
Resin	Current	Polyester			1,50	99,0	148,5	148,5
	Alternative	ONE High Biobased Laminating Epoxy			1,50	99,0	148,5	148,5
Core	Current	PVC70/ 20mm	75		1,50	93,0	139,5	0,0
	Alternative	Baltex SBC 19,1mm	109		2,10	93,0	195,3	0,0
Inner Skin	Current	E-CSM 450gm	450	5	1,50	514,5	763,9	540,2
	Alternative	Basalt fibre surface mat	100	20	0,33	2079	686,0	485,1

3.3 Material selection

The current boat has made of e-glass fibre, which is the most common material in the boat industry and our case; it was the most expedient solution. First, there was a desire to build the boat conventionally as light as possible, but staying in the target weight. However, on the other hand, it had to be as cheap as possible. Meanwhile boat physical strength characteristics could not be suffered or reduced, turning that process. Combining these parameters, it was economic sense to use E-glass that is why the carbon and Kevlar fibre were out of selection. E-glass has reasonable strength/weight/cost ratio, for that reason, it is popular on boat building industries. The carbon and aramid fibres are more usable in a high-performance item, where weight-strength ratio is crucial.

For lamination processes, has used vacuum infusion. The reason for that is to have a high-quality product, thick solid lamination, material layout and overlapping or a certain amount of resin in the laminations process. Vacuum infusion will also help to speed up the processing time, improve the product quality and reduce wasting. The vacuum infusion allows reducing, with the same mechanical properties, the total weight of the yacht of about 9% and the weight reduction is about 25% in the total structure, over the hand lay-up. This technique has advantages in terms of construction, since there is a reduction of raw material use, will reduce the total cost and weight, while in disposal phase, the less material will go to landfill. An important parameter that influences the weight of the manufacture is the ratio between the fibre weight and the total laminate weight for a unit of composite. This ratio is indicated the glass content, wherein the hand lay-up, this value is assessed by weighing, in about 0,40%, but with vacuum infusion technique, the value of this ratio is about 0,65%. Therefore, for the same weight of the composite, the quantity of glass fibre is higher (Cucinotta, Guglielmino, & Sfravara, 2017). In the production, the fibre content in the hull and deck is 60% and in the bulkheads 50%. The vacuum infusion is used in 37 ft. yacht production, the resin consumptions are estimated to reduce 267 kg, compared with hand layup.

Table 3 Resin consumption difference between vacuum infusion and hand layup

Resin consumptions	**Deck**	**Hull**	**Interior bulkheads**
Hand layup (resin consumption with fibre content 40%) kg	252	430	36
Vacuum infusion (current resin consumption) kg	174	250	27
Difference kg	**78**	**180**	**9**

The lamination schema has been used three different types of core material: solid, foam and plywood, which were used on the different areas of the boat. The sandwich with core material PVC foam 20 mm Aritex 75, use to increase stiffness with thickness, the further are surface elements from the neutralizer as core body, the greater is the inflexibility. Also the sandwich could save the total weight of the boat but limiting the subsequent opportunity to installing the hardware in the future or cannot handle the high load on sideways. This 37 ft. yacht hull and deck consist of ca 90-95% sandwich laminations, e.g. hull total surface is 56 m^2 where solid laminations area is 2,6 m^2 and deck total surface area is 43 m^2 and solid laminations area is 2,6 m^2. The solid lamination has used on areas where extra stiffness is required or near the edges and corners, where are challenging to handle thick material to make proper radiuses. All the bases that have to handle high load are made of solid laminate, e.g. area where the keel is attached and all hardware like winches and blocks. In Figure 3.5 can be seen the red area has sandwich lamination, and the green area is made of a single skin.

Figure 3.5 The laminated deck upside down.

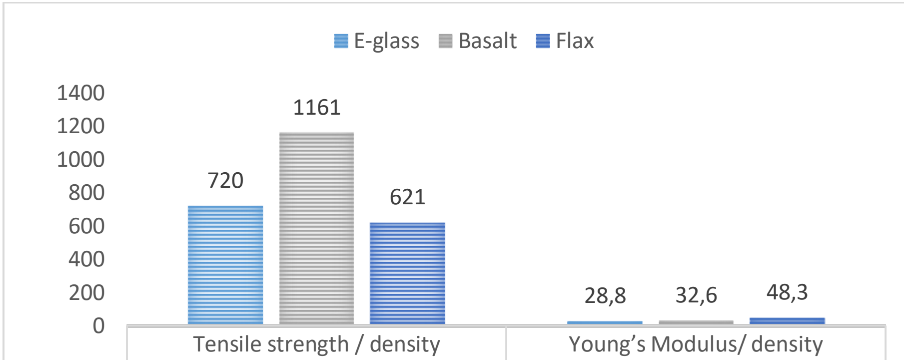
The lamination lay-up of the deck and hull can be a divided into four layers. Skin coat, outer skin, core and inner skin, that is described in Table 3.3, the full lay-up schema are described in appendix 1 and 2. The first layer will be painted. The easiest way is to cover mould with Gelcoat. Which is 0,5-0,8 mm paint and based on epoxy, which makes them durable and lasting paints, then glass fibre chopped strand mat will be added to bond the Gelcoat paint and fibre fabric. This first layer might be varieties the demands of the customer and if hull colour with different paint pigments or sophisticated design elements is requested, this case the Gelcoat will not be used.

Table 3.3 Hull and deck layup

Hull Layup 37 ft. Yacht				**Deck Layup 37 ft. Yacht**			
Description	**Layer**	**Material**	**Fibre orientation referred**	**Description**	**Layer**	**Material**	**Fibre orientation referred**
Skin coat	0	Paint		Skin coat	0	Gel Coat	
Outer Skin	1	E-UD 300	90°		1	CSM 300	/
	2	E-UD 300	0°		3	CSM 225	/
	3	E-UD 300	90°	Outer Skin	4	E-WR 300	0-90°
	4	E-UD 300	0°		5	E-UD 300	0
	5	E-UD 300	90°		6	E-UD 300	90
	6	E-DB 400	+-45°		7	E-DB 300	+-45°
	7	E-DB 400	+-45°		8	E-DB 300	+-45°
Core	PVC	PVC75 / 20mm		Core	PVC	PVC75/ 20mm	
	PVC	PVC130 / 20mm			PVC	PVC 200/Marine Plywood	
	Single skin	QX E 1200			Single skin	QX E 1200	
Inner Skin	8	E-DB 400	+-45°	Inner Skin	9	E-DB 300	+-45°
	9	E-DB 400	+-45°		10	E-DB 300	+-45°
	10	E-UD 300	90°		11	E-UD 300	90
	11	E-UD 300	0°		12	E-UD 300	0
	12	E-UD 300	90°		13	E-WR 300	0-90°
	13	E-UD 300	0°				
	14	E-UD 300	90°				

In the hull and deck laminations are several layers of unidirectional and bidirectional oriented glass fibre, to have more strength on the hull and deck. Usually, unidirectional oriented glass fibre composites have more compressive strength, tensile strength, than bidirectional (Tanwer, 2014). Using vacuum infusion give options to direct precisely the fibres alignment, to archive the maximum strength of lamination. While in hand lay-up the direction may move during rolling of the fabric. The current lay-up of the deck and inner skin has used mainly unidirectional glass fibre fabrics with layup variation 0° and 90° and double direction fabrics (typically +/- 45°). The outer skin is a vice-verse copy of inner skin, and the lay-up will remain the same. As core material has used Airex 20 mm PVC 75, PVC130, PVC200 or as single skin E-glass quad-axial. The single skin has used in high load area and is placed with several layers.

A good alternative for replacing the e-glass to more sustainable material is one of the strongest natural fibre: the flax. A Swiss company, Bcomp is a leading natural fibre composite innovator. Their product "ampliTex Non-crimp", it the strongest and stiffest natural fibre composites on the market, that fit on highly automated manufacturing process (bcomp, 2020). Flax is good natural fibre reinforcement because it is easy to handle, has good mechanical properties, good change bonding with polymer matrices. These fibres have a low density, are incredibly light and at the same time, the tensile is comparable to glass fibres. It makes flax is a promising natural fibre in boat production. It is a highly productive plant. The density is 1,45 g/cm^3, which is half of the weight compared to E-glass fibre 2,5 g/cm^3. Flax tensile strength is 500-900 MPa and E-glass 1200-1800 MPa, which is twice a bigger, but have to consider that flax is approximately 40% lighter material. The density of a material is a crucial consideration in the application as a lower weight material could reduce costs in some areas of the boat. In density and tensile strength ratio with glass fibre advantage is marginal. The flex is a relatively stiff and strong material. Have highly impact resistant and more resistant to abrasion than E-glass fibre or carbon. The specific strength, the strength-to-weight ratio is not so bad comparing e-glass, and young modulus is better with density comparison than Specific stiffness in tension in Figure 3.6. Flax fabric issue is, that fibre weight with 60% content can be achieved with process pressure > 5 bars, comparing with e-glass the pressure is around one bar. However, the natural fibres absorb a lot of resin, and when hand laminating are used; it tends to look "dry" before the pressure is applied. For this reason on new lay-up schema, the fibre content is reduced to 50%, and it would be challenging to achieve a similar result as with fibreglass.



	Tensile strength / density	Young's Modulus/ density
E-glass	720	28,8
Basalt	1161	32,6
Flax	621	48,3

Figure 3.6 Specific strength and specific stiffness

In Table 3.4 and 3.5 are described new layup, where e-glass is replaced with flex, the core material PVC foam with balsa and vinyl ester is changed to bio-based epoxy (new full lay-up schema is described in appendix 6 and 8). The replacement of fabric has done on principle, that substitution is a similar as possible, but the fibre yarn direction and densities remain the same. Increase the density of flax fabric, will increase the tensile strength of the laminate.

Both deck and hull layup has slightly modified. The areas where stress is higher has added an extra layer of fabric to increase the total strength. Transversal strip layers around the mast collar and longitudinal strip on the deck and coach roof, has increase the laminar on deck by 47 m^2, on the hull has added one layer transversal strip around the keel and mast step, the on bottom of the boat, the total laminar of hull increase 82 m^2.

Table 3.4 Hull new layup with flax fibre

Hull Layup 37 ft.		**ONE High bio-based Laminating Epoxy**			**Hull total surface = 56 m²**		
Layer	**Material**	**Fibre orientation**	**N° of layers**	**Fibre Cont.** %	**Lam. weight unit.** [kg/m²]	**Lam. Weight tot.** kg	**Resin** kg
Skin coat	Vinyl ester Base & Paint		1		0,70	39,2	
Outer Skin	ampliTex 5025 UD300	90°	1	50%	0,50	33,9	16,9
	ampliTex 5025 UD300	0°	1	50%	0,50	33,9	16,9
	ampliTex 5025 UD300	90°	1	50%	0,50	22,2	11,1
	ampliTex 5025 UD300	0°	4	50%	0,50	72,0	36,0
	ampliTex 5025 UD300	90°	3	50%	0,50	19,8	9,9
	ampliTex5008 DB 350	+-45°	1	50%	0,58	40,7	20,4
	ampliTex5008 DB 350	+-45°	2	50%	0,58	10,2	5,1
Resin	Resin uptake				1,50	84,0	84,0
Balsa	Balsa 19mm				2,07	113,9	0,0
Single skin	ampliTex5008 DB 350	+-45°	35	50%	2,00	66,2	33,1
Inner Skin	ampliTex5008 DB 350	+-45°	2	50%	0,58	10,2	5,1
	ampliTex5008 DB 350	+-45°	1	50%	0,58	40,7	20,4
	ampliTex 5025 UD300	90°	3	50%	0,50	19,8	9,9
	ampliTex 5025 UD300	0°	4	50%	0,50	72,0	36,0
	ampliTex 5025 UD300	90°	1	50%	0,50	22,2	11,1
	ampliTex 5025 UD300	0°	1	50%	0,50	33,9	16,9
	ampliTex 5025 UD300	90°	1	50%	0,50	33,9	16,9
			total weight =			**769,0**	**350,0**

Table 3.5 New deck lamination layup with flax

Deck Layup 37 ft. Yacht		**ONE High Biobased Laminating Epoxy**			**Deck total surface = 43 m²**		
Layer	**Material**	**Fibre orientation**	**N° of layers**	**Fibre Cont.**	**Lam. weight unit.**	**Lam. Weight tot.**	**Resin**
				%	[kg/m²]	kg	kg
Skin coat	Gel Coat		1	100%	0,96	41,3	
	ampliTex 5025 DB	/	1	30%	1,17	52,1	36,5
	ampliTex 5025 DB	/	1	30%	1,17	10,5	7,4
Outer Skin	ampliTex 5040 twill WR	0-90°	1	50%	0,60	26,8	13,4
	ampliTex 5008 UB	0	3	50%	0,60	28,4	14,2
	ampliTex 5008 UB	90	3	50%	0,60	13,7	6,8
	ampliTex 5025 DB	+-45°	1	50%	0,70	31,3	15,6
	ampliTex 5025 DB	+-45°	3	50%	0,70	10,9	5,5
Resin	Resin uptake				1,50	64,5	64,5
Core	Balsa SBC.50 19 mm				2,07	82,8	0,0
	Balsa SBC.100 19 mm				2,82	2,8	0,0
	ampliTex 5025 DB	+-45°	7	50%	0,70	10,2	5,1
Inner Skin	ampliTex 5025 DB	+-45°	3	50%	0,70	10,9	5,5
	ampliTex 5025 DB	+-45°	1	50%	0,70	31,3	15,6
	ampliTex 5008 UB	90	3	50%	0,60	9,1	4,6
	ampliTex 5008 UB	0	3	50%	0,60	19,0	9,5
	ampliTex 5040 twill	0-90°	1	50%	0,60	27,1	13,5
					total weight =	**479**	**220**

Since the lamination content is reduced from 60 to 50%, the hull and deck total weight increased mostly by resin consumption. The other issue of using flax is that fabrics supplying is limited, because it is challenging to find different yarns and fabric density. Have solid laminate with high density, the more layers are required, than e-glass lamination, e.g. to replace ten layers of 1200 g/m^2 quadriaxial laminar, should be use approximately 35 layers of biaxial flax with density 350 g/m^2. Taking into the account overlapping of material, the total fabric consumption increase with resin consumption. In this case, on E-glass fibres market are more opportunities. With new lamentation lay-up, the deck weight increased from 396 kg to 479 kg, where 48 kg of increase is related to the resin. The hull weight change was from 650 kg to 769 kg, and the resin increase was 100 kg.

The other advances natural fibre is basalt, which is made from extremely fine fibres of basalt and has been produced from hard volcanic rock. It has better mechanical properties than fibreglass, but being significantly cheaper than carbon fibre, meanwhile, it is material with a low ecological footprint, good heat performance and excellent chemical resistance. Since there is no boron or any other alkali metal oxide generated in melting down the basalt, the production process of basalt fibre does not generate any pollutant, which makes it a new environment-friendly fibre in the 21st century (Zhang, Tang, Pu, & Zhang, 2011). Basalt has used on boats, it is a new trend in racing boat sector to build light and strong boat from basalt. Basalt fibre has low water absorption, which is essential in the yacht building sector. As other natural fibres, the basalt fibre manufacturers have less direct control over the purity and consistency of the raw basalt stone. In chopped mat, roving and unidirectional fabric forms, basalt fibres exhibit a higher breaking load and higher Young's modulus than E-glass (Ross, 2006). Basalt fibres are naturally resistant to ultraviolet (UV), which is good of sailing point of view. Also, basalt fibres wet easily and therefore enable fast resin impregnation, which makes possible to produce a reinforced fibre with high fibre content.

Basalt has the highest specific strength comparing e-glass or flax. It has already proven as a quality material in the yacht industry. There are some prototypes racing yachts, which are made from basalt fibre. Basalt production and most marketing efforts are based in countries that are related to the post-Soviet Union countries, e.g. Russia and Ukraine. There are many distributors around the world, but their sources are limited. It also applies the existence of fibre fabric, and it seems the basalt fabric are produced pull method, because the distributors have several different fabrics in the portfolio, but they are ordered to make them the most. It makes the choices of fabric density very short on the market, which in turn complicates the design and construction of the sailboat because comparing it with E-glass, there are fewer offers on the market. In Table 3.6 and 3.7 are described the new layup and full described in Appendix 7 and 9. There has been following the same principles as an original layup, and the fabric directions are remained the same, the fibre density is increased to 350 g/m^2 and 450 g/m^2, due to the lack of smaller density fibre. Some of the layers are removed but has been replaced with higher density fibre. Generally, the total amount of laminar is remained the same. The total weight of hull increase 14 kg but this is mainly because of balsa which has more density than PVC foam and deck weight increase 35 kg, this mainly because of balsa and basalt higher density in the layers.

Table 3.6. Basalt hull layup

Hull Layup 37 ft.		**ONE High bio-based Laminating Epoxy**			**Hull total surface = 56 m²**		
Layer	**Material**	**Fibre orientation**	**N° of layers**	**Fibre Cont.**	**Lam. weight unit.**	**Lam. Weight tot.**	**Resin**
				%	[kg/m²]	kg	kg
Skin coat	Base & Paint		1		0,70	39,2	
Outer Skin	Basalt UD350	90°	1	60%	0,58	32,9	13,2
	Basalt UD350	0°	1	60%	0,58	32,9	13,2
	Basalt UD350	90°	1	60%	0,58	21,6	8,6
	Basalt UD350	0°	2	60%	0,58	35,0	14,0
	Basalt UD350	90°	2	60%	0,58	12,8	5,1
	Basalt BI450	+-45°	1	60%	0,58	43,7	17,5
	Basalt BI450	+-45°	2	60%	0,58	5,5	2,2
Resin	Resin uptake				1,50	84,0	84,0
Balsa	Balsa 19 mm SCB				2,07	113,9	0,0
Single skin	Basalt QX 1000	+-45°	10	60%	2,00	45,0	18,0
Inner Skin	Basalt BI450	+-45°	2	60%	0,58	5,5	2,2
	Basalt BI450	+-45°	1	60%	0,58	43,7	17,5
	Basalt UD350	90°	2	60%	0,58	12,8	5,1
	Basalt UD350	0°	2	60%	0,58	35,0	14,0
	Basalt UD350	90°	1	60%	0,58	21,6	8,6
	Basalt UD350	0°	1	60%	0,58	32,9	13,2
	Basalt UD350	90°	1	60%	0,58	32,9	13,2
				total weight =		**651**	**250**

Table 3.7. Basalt deck layup

Deck Layup 37 ft. Yacht		**ONE High Biobased Laminating Epoxy**			**Deck total surface = 43 m²**		
Layer	**Material**	**Fibre orientation**	**N° of layers**	**Fibre Cont.%**	**Lam. weight unit. [kg/m²]**	**Lam. Weight tot. Kg**	**Resin kg**
Skin coat	Gel Coat		1	100%	0,96	41,3	
	Basalt DB450	/	1	30%	1,00	67,0	46,9
	Basalt WR350	0-90°	1	60%	0,58	26,1	10,4
Outer Skin	Basalt UD350	0	2	60%	0,58	9,2	3,7
	Basalt UD350	90	2	60%	0,58	8,9	3,5
	Basalt DB450	+-45°	1	60%	0,75	33,5	13,4
	Basalt DB600	+-45°	1	60%	1,00	5,2	2,1
Resin	Resin uptake				1,50	64,5	64,5
Balsa	Balsa SBC.50 19 mm				2,07	82,8	0,0
	Balsa SBC.100 19 mm				2,82	2,8	0,0
Single skin	Basalt QUADRI		2	60%	4,00	6,9	2,8
Inner Skin	Basalt DB600	+-45°	1	60%	1,00	5,2	2,1
	Basalt DB450	+-45°	1	60%	0,75	33,5	13,4
	Basalt UD350	90	2	60%	0,58	8,9	3,5
	Basalt UD350	0	2	60%	0,58	9,2	3,7
	Basalt WR350	0-90°	1	60%	0,58	26,1	10,4
				total weight =		**431**	**180**

The original boat sandwich are made from 20 mm PVC 75 and in the bow, which is the slamming area in the waves, is used PVC130, it is 10 m^2 of the total area of the hull. On deck has been used 1 m^2 of PVC 200 on the bow section, where are high loads is produced by forestay tensions and slamming waves. The chosen foam has closed-cell, which combines excellent stiffness and strength to weight ratios with superior toughness. It has negligible water absorption, which makes it perfect to use in yacht structure. Also, it has low resin absorption and excellent bonding surface to make the material easy to handle. Comparing PVC 130 with PVC 75, the first one has a twice of compressive strength and Tensile strength perpendicular to the plane (Table 3.8.). The excellent alternative for increasing sustainability is to replace Airex polymer foam to balsa BALTEK SBC, which is a natural material and has FSC-certification. Replacing the Airex polymer foam to balsa BALTEK SBC will increase hull weight by 20,4 kg, and deck weight increases by 15,6 kg because of the higher density of balsa. Balsa is excellent material also because of his handling ability, because it is essentially wood and with it is possible to use wood manufacturing techniques. Considering the lightness, it could mix modern boat building and traditional techniques, to archive completive composite sandwich panel.

Table 3.8. Typical properties of core materials (3acorematerials, 2020) (Buefa, 2020)

Typical properties of core materials	**Compressive strength perpendicular to the plane N/mm²**	**Tensile strength in the plane N/mm²**	**Density kg/m³**
AIREX C70.75	1,45	2,0	80
AIREX C70.130	3,0	4,0	130
AIREX C70.200	5,2	6,0	200
BALTEK SBC.50	5,5	3,9	109
BALTEK SBC.100	9,2	5,7	148

As a resin is used Atlac 580 AC 300 which is a pre-accelerated vinyl ester urethane resin, is known as conventional fossil-based resin. It has a low peak exothermic development during the curing process and low viscosity, which makes it easy to handle in vacuum injection. This resin is specially designed for the production of fibre-reinforced boats. The reason why in the original boat is made of vinyl ester is the lower cost, comparing the standard epoxy resin.

Also, the current vinyl ester resins on the market have gone through some development, when in terms of physical characteristics, they are not any more so poor compared with epoxy. The issue with the vinyl ester is that in the post-curing process the resin will shrink. For this reason, it is essential to heat the product and bake it through. Otherwise, the post-curing might take place after the boat has launched on the water and then the sun will heat the resin temperature, which will damage the paint or Gelcoat. There are developed renewable vinyl ester resins, there are articles of that, but there are challenging to find it and buy from the market. It seems that so far, the fossil-based vinyl ester seems cheap and that it is difficult to make a change in consumers demand, that might be the reason that bio-based epoxy is more known and available on the market. In our production, the acceptable alternative replacement for vinyl ester can be the One High bio-based Laminating Epoxy, which is designed for composites, coating, and adhesive applications. Bio-based Epoxy resin is a product of 30% from carbon plant origin and has a lower environmental impact than standard epoxy resins. In general, epoxy shrinks less than polyester and vinyl ester resins, on bio-based epoxy it may vary, because of the content of natural material. In general, comparing the properties of resins, the differences are not big, the epoxy has some worst figures. e.g. flexural strength, but since there a no extreme bending on the hull, that parameter would not be an issue, the density is the same. Tensile modulus, what is measures the stiffness and compression, is similar. Tensile strength level under stress has bio-based epoxy slightly lower.

Table 3.9. Properties of resins

Properties of resins	Atlac 580 AC 300	ONE High Biobased Laminating Epoxy
Tensile Modulus MPa	3.0	3.2
Tensile Strength MPa	78	67.6
Elongation at break	3,4%	6%
Density	1,08	1,09
Flexural Strength MPa	150	100.5

All the bulkheads are made of composite sandwich or marine plywood, and they are laminated to the hull and deck. It makes boat structure monocoque, extra stiff and long-lasting, where deck and hull are bonded together. In monocoque, the skin is part of the structural system, where loads are supported through an object's external skin via internal structure. Semi monocoque construction is used for yachts where bulkheads and deck/hull are not laminated together. Usually glued together with Sikaflex or resin filler and working on compression and tension. It makes even complicated to put a yacht on the dry dock, where cradle supporting beams have to set up under the bulkheads to avoid any damage of lamination. With full laminations, the boat structural element can be protected from high humanity and water damage, which may accumulate in the bilge. The baldheads start to absorb water, which causes delamination and strength loss of fibre, and natural fibres can start slightly to rot.

The downside, when bulkheads are laminated to the hull and deck, is related with disassembly. If a boat has reached EOL, the recycling is more complicated, because all panels are bonded to the hull and removing can be done via cutting. The cutting process excretes a lot of glass fibre dust, which is extremely dangerous to human by inhalation. Soreness in the nose and throat can result when fibre dust is inhaled. The fibreglass dust can cause asthma and bronchitis or other lung diseases. It limits the possibilities for recycling, where partial dismantling or process in stages is difficult to carry out. Without this limitation can be an option, where sailboat can be cut into pieces, the pieces will be transferred to a recycling point to save cost. For that case, the natural fibres can be a solution to reduce environmental contamination during recycling.

Figure 3.7 Bulkheads are bonded to the hull

The current bulkheads mainly made of e-glass skin and PVC foam core, for replacement can be use balsa core and flax fibre fabric, the same solution as were proposed before for hull and deck lamination. The fibre content remains the same as initial, 50%. In original layup was made of mostly 400 g/m^2 biaxial glass fibre, for new layup it is changed to 350 g/m^2 with an extra layer on every panel to increase the strength of the bulkhead and hull. Using glass fibre the bulkhead weight where 59,5 kg and it stays the same flax, but this is because of some planes, what originally supposed to be made of plywood should be made of balsa. 15 mm balsa weight is 1,63 kg/m^2, what is similar to 15 mm PVC, which weight 1,50 kg/m^2. The other option to use alternative materials is basalt fibre with balsa core, and the layup remains on the same conditions as was proposed in last change. Due to the fact, basalt has better mechanical properties than flax, e-glass, the lay-up has slightly modified, and some layer is removed, to reduce density. In Figure 3.8 are described the effects of changing bulkheads material, the full new lay-up are described on appendixes 10-15. Flax lamination area is increased because of extra layers, what has been added to increase the strength and lamination weight on the same level original layup.

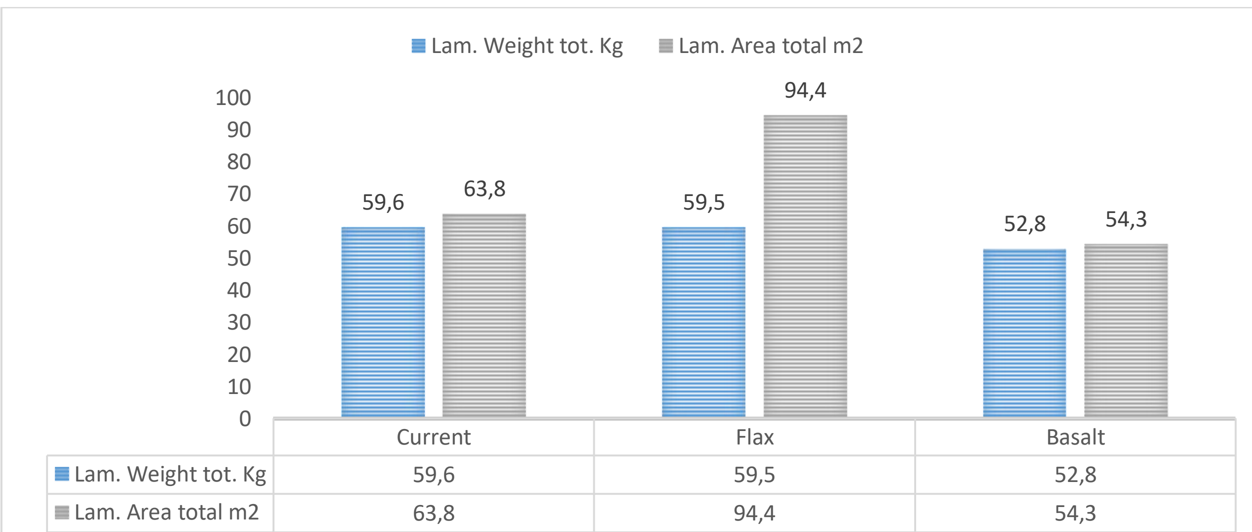


Figure 3.8 E-glass, Flax and Basalt bulkhead lamination weight and area

The current boat has carbon fibre rigging (mast, spinnaker boom and boom) and is chosen because of the low weight of the material, the lower is weight in the rig, the more increases righting moment and performance, high stiffness improves the control of mast bend, which improve the sail shape, high tensile strength increases the durability in extreme situations. The excellent strength-weight ratio on carbon mast will allow to design and construct a lighter boat with less ballast. Carbon is expensive compared with similar fibres, such as glass fibres or Kevlar fibres. In the use of carbon there are also differences of the strength of the material, e.g. high modulus carbon, comparing with the regular carbon the mast tube could be 10-20% lighter, but also the price is higher. In this case is used regular carbon. Current carbon mast what is on the boat weights 136 kg, this includes standing rigging and mast centre of gravity from step is ca 7,4 m. Meanwhile aluminium mast could weight ca 180 kg and mast centre of gravity from step approximately 8,30 m. The advantages of carbon fibre do not exceed the low price of the aluminium mast. That is the reason why it is the most commonly used material for the mast in the yachting sector. For sure, the aluminium is recyclable, nonetheless a non-renewable resource. However, it is interesting about the aluminium, to producing it from the ore is 95% more energy-intensive process, than recycling.

4. ANALYSIS

The sailboat production has many invisible areas, which are not visible to all parties, who participate in yacht production or later the consumption of the product. The wastes begin to be generated immediately at the beginning of the processes. After every stage, a certain amount of rubbish accumulates, which should be handled in the most environmentally friendly way. Also, wastes should be generated responsibly and think about what will happen later. It is essential to understand, the eco-friendliness will not only start, when a boat arrived at the end of life phase, it begins when production starts. Therefore, it must be payed attention on waste management at the beginning of the production phase.

To start from really beginning, replacing the regular low formaldehyde MDF to Ecoboard which is No Added formaldehyde MDF. The price difference is marginal, for instance 12 mm MFD cost 5,71 €/m^2, while Ecoboard cost 5,75 €/m^2. This is not huge cost to reduce formaldehyde in MFD and what will be landfilled with construction wastes or will be incinerated. Considering that plug is for single-use, after the use, it should be recycled in the best way. Of course, different coatings and fillers must still be treated as hazardous wastes. The intertwining of surface layers makes their recycling processing more difficult.

Mould is by its nature a classical GRP product, which one side is coated with gel coat paint. Replacing with basalt makes it slightly more eco-friendly, but also could affect the cost of the moulds. Basalt rock, the raw material of fibre fabric is the product of the volcanic activity, so the fabrication process is more eco-friendly than glass fibre production. The greenhouse gases what usually will be released during fibre processing were vented to the air millions of years ago during the volcanic magma eruption. On the recycling point of view, the problem will remain the same as glass fibre, and then the boat arrives at EOL, the methods and recyclability are same. The replacement of the glass fibre to basalt surface mat 100 g/m2 and using bio-based epoxy will be also expensive and increase the total cost of moulds. It is challenging to find bio-based resin and which is suitable for the use marine sector is the reason, why ONE High bio-based Laminating Epoxy is selected. There are some 100% biodegradable polyester and vinyl ester on the market, which are cheaper, but they are intended for use in plywoods, and their durability in corrosion environment might be questionable. There should be considered the fact that mould can be maintained in outdoor conditions, in that case, the same requirements are applied on moulds as for a sailboat. In Figure 4.1 are described the deck and hull mould fibre and resin total cost, comparing e-glass.

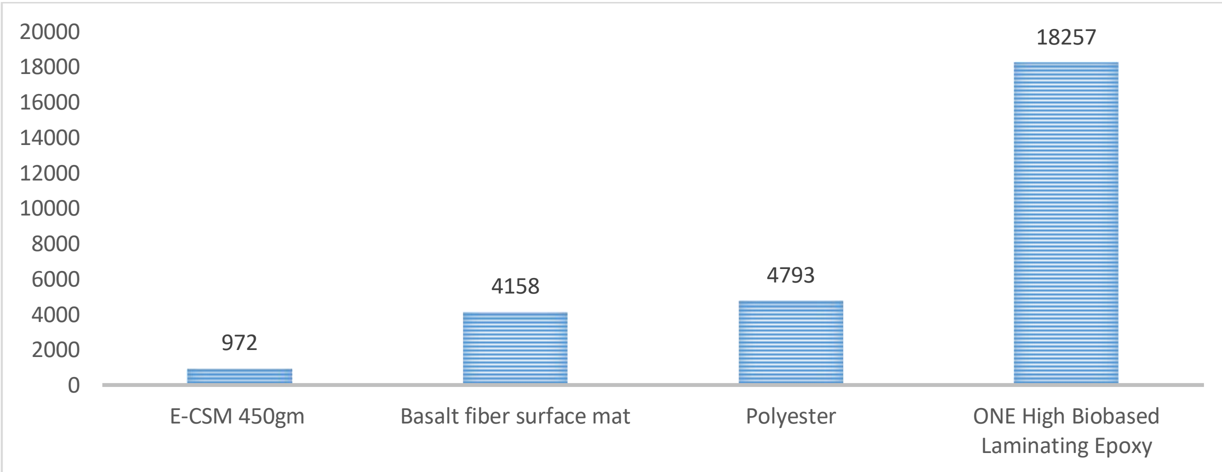
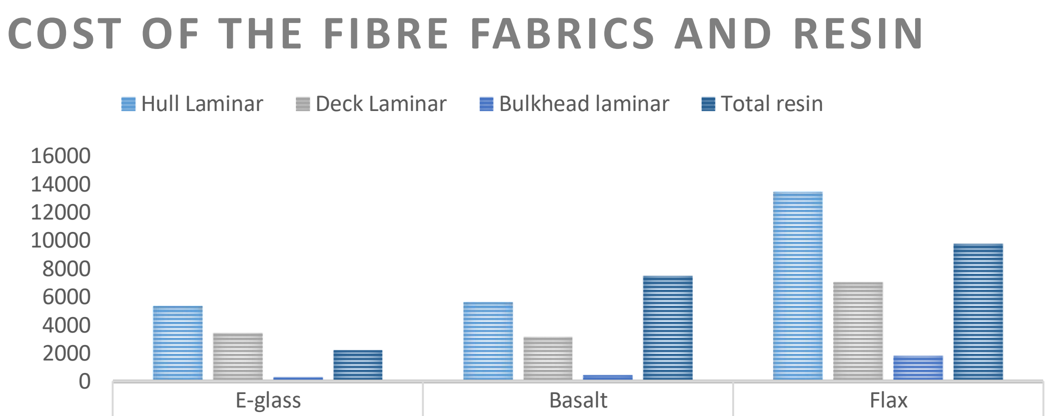


Figure 4.1 Deck and hull mould fibre and resin total cost

Choosing the eco-friendly material basalt and flax for boat lamination, were selected for specific reasons. The basalt is a new trendy material in the yacht industry, which is proposed as a substitute material for e-glass or carbon fibre. It has good physical properties, and yet it is considered an eco-friendly material. The other material is flax, which is entirely natural and has strong potential reinforced fibre plastic sector. On physical properties, it has less strength, but meanwhile, it has also less density, but comparing specific strength (tensile strength and density) ratio the flax performance is completive with e-glass. Balsa as a core is forgotten new-old material.

Replacing glass fibre to basalt or flax both will give double results, which are very different (described in Figure 4.2.). Comparing laminar basalt cost of deck and hull, the contrast between glass fibre laminar products is not much. The general cost will keep down by balsa unit price 34,5 €/m^2, which is twice as cheap as PVC foam 70 €/m^2. Even the new basalt layup schema reduced a little bit and has less laminar consumption, the cost of total basalt is still higher than glass fibre. The basalt fabric cost for the hull is 3730 € and cost with e-glass is 1434 €. The basalt cost on deck is 1764 € and with e-glass 619 €. Using the basalt will increase the laminar cost. Even basalt has higher physical properties, which allow reducing the layers in layup schema and cost of material, the basalt price per kilogram is still relatively higher than e-glass. Besides, there is limited fabric selection on the market, designers and boat builders might have an issue to found needed density and quality of the fabric.



	E-glass	Basalt	Flax
Hull Laminar	5335	5628	13432
Deck Laminar	3444	3179	7011
Bulkhead laminar	329	454	1830
Total resin	2213	7472	9777

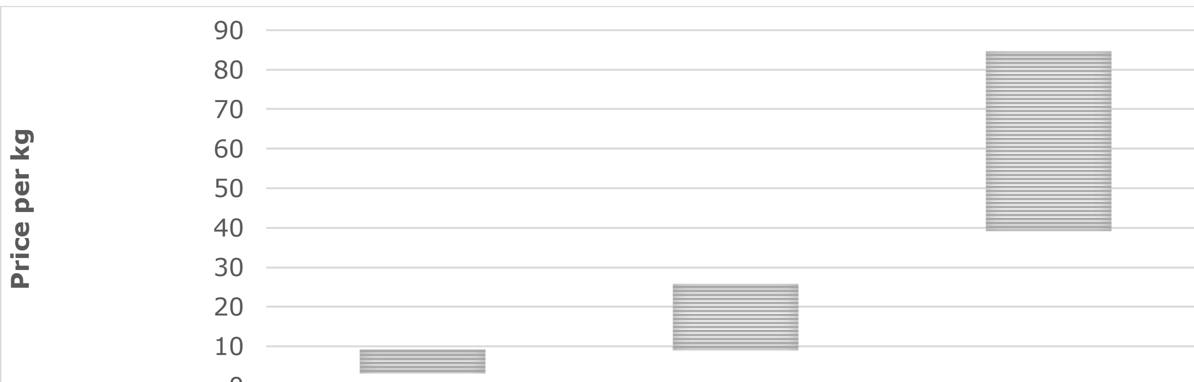
Figure 4.2. Cost of the fibre fabrics and resin with core material

Considering the e-glass and basalt has similar density, the other issue what comes using basalt is related to sandwich outer skin thickness. In original hull layup, some outer skin areas have only three layers of fabric, which total thickness is approximately 0,88 mm and paint, which is 1 mm. Removing the basalt layer will reduce thickness and risk if outer skin will be damaged; the core material can absorb moisture and water. Especially when the core material is balsa, which is a natural material. Moist in the core will cause delamination of a sandwich.

Considering the previous flax good implementation, the comparison of flax and e-glass results were surprising and concerning. Comparing laminar flax cost of deck and hull, the contrast between glass fibre laminar products is high. Using the balsa core, the cost will be decreased, but the laminar cost itself of hull, deck and bulkheads are increased. Using flax, the laminar cost of the hull is 11536 €; meanwhile, e-glass cost was 1434 €, and deck cost has increased to 5597 € from 619 €, even bulkhead has a significant increase of the cost.

There are several issues, first, it seems high-performance flax is extremely expensive, comparing with e-glass. The second issue is that flax fabric absorbs much resin. For that reason, the fibre content is reduced to 50%, and it would be complicated to achieve a similar result as with fibreglass. It is confirmed by the manufacturer's instructions the fibre weight with 60% requires 6 bar vacuum. It will increase the resin consumption and the higher total cost of resin. The resin cost has also affected by the replacement of adhesive, because vinyl ester the retail price is 5 €/kg, then replaced epoxy unit price is 16,3 €/kg, which is an enormous difference, but not to reduce the durability, there is selected epoxy which is suitable for marine items. The third issue is similar with basalt since it is a natural material, the quality variates and fabric selection is restricted. It can lead to a situation in the construction process, due to the lack of material the material substitution is only and challenging option to amplify the product or re-design. It has also happened with our case, not to lose strength in layup schema, there is used more layers, which increase the price, especially when flax is used.

A general problem for using natural material instead of fibreglass is mainly related to price and durability. Comparing E-glass, basalt and Flax kilogram price in Figure 4.3, the differences are large, and there is no doubt in favour of using an E-glass. Considering the basalt physical properties, it should be a good replacement for S-glass or carbon fibre products, and in this section, the unit price is more completive. The E-glass price difference per kg with flax is even bigger. Flax has been advertised as light and with slightly weaker properties than e-glass, but compared to the specific strength and price per kilogram. In this case, it is an expensive material. Also, it is worth mentioning that carbon and flax mixed fibre fabric retail price is approximately 166,5 €/kg. Flax advantage is the lightness, that is why it is good to use for non-structural purposes, e.g. inside the modules or furniture panels.



	E-glass	Basalt	Flax
Maximum kg price	6	16,71	45,33
Minimum kg price	3,3	9,16	39,23

Figure 4.3 E-glass, basalt and flax price comparison per kilogram

Comparing the change in costs and the overall impact of the material on the price of the sailboat is described in Table 4.1, prices are based on purchase prices and do not include labour costs of producing the boat. Initial total cost 228 382 €, it is important to note, that hull plug and mould is outsourced, including the associated labour costs, which is the reason, why the cost of the item is very high. There has made estimated cost change, then e-glass fibre, polyester and PVC foam will be replaced with basalt, bio-based epoxy resin and balsa. Meanwhile, the deck plug and mould cost row is only related to material consumption.

The table clearly shows an increase in the total cost of using alternative materials. On an initial boat, the hull, deck and bulkheads raw material total cost was 18 497 €, using basalt, balsa core and bio-based epoxy, the cost increased to 23 639 €, replacing e-glass to the flax the cost increased to the 39 227 €. Large save occurred due to mast change, which helped to make the total cost more competitive comparing with an initial total cost because aluminium spar is much cheaper than carbon spar.

Table 4.1 Statement of material expenditure

Cost section	Cost with e-glass and PVC foam	Cost with basalt and balsa core	Cost with flax and balsa core
Hull plug CNC machined and mould	€ 50 000	€ 57 813	€ 57 813
Deck plug and mould	€ 16 500	€ 22 500	€ 22 500
Deck materials for infusion	€ 7 170	€ 8 829	€ 13 493
Hull materials for infusion	€ 9 566	€ 12 681	€ 22 121
Bulkheads and templates	€ 1 761	€ 2 129	€ 3 613
Spar	€ 40 000	€ 13 500	€ 13 500
Other	€ 103 385	€ 103 385	€ 103 385
Total	**€ 228 382**	**€ 220 837**	**€ 236 425**

The replacement impact may be different, depending on the customer request and as well as the manufacturer chooses. Considering the final total cost, the percent different from the initial cost is marginal. Therefore, in summary, the choice of material is playing an essential a role by the demand and the way of marketing. As in other areas of life are communities with “green” or eco-friendly thinking, they always prefers to consume eco-friendly products, a similar community could occur among with sailing.

SUMMARY

The boat building industry has changed a lot in the last decades, because of new synthetic materials, like fibre-reinforced polymer-based composites (FRP) has been affecting the boat building industry. FRP is having a significant increase in boat building and marine construction industries because it is the optimum choice in terms of durability, workability and cost. Material is also resistant to the UV, seawater, fatigue loads and has a high strength-to-weight ratio, which makes it perfect material in this sector. The material durability has caused the postponement when boats will arrive at the end-of-life and need to be recycled, but the problem with EOL boat in point of view in waste management, have been practically not evaluated and not conscious. There is around 6 million leisure craft, which needs to be recycled one day. In a low environmental impact perspective, the other sectors have made the more progressive step, for example, is the automotive industry is far ahead comparing boat-building industry.

Thesis focus on 37 ft. yacht production and improvement for more eco-friendly that after the boat has reached the EOL for the dismantling, the impact on the environment would be as small as possible. Also, to evaluate how does it affect the total cost of the boat and market competitiveness.

Solutions, making yacht building sustainable and eco-friendly were found, that there are several options for this, different material manufacturers are trying to increase eco-friendliness in the products and bringing new products to market. Particular interest has the new entry of natural fibres on the market, with high effort on research and development; it has increase natural fibres performance. There are more and more projects where natural fibres are used, but unfortunately those are so far only prototypes. Thus, general information and literature of using natural fibres about the success and setbacks of these prototypes are not available. Problem might be to find bio gradable materials, which is suitable for marine sector, what handle the high moisture and last long as e-glass.

Opinions to make yacht more recyclable were proposed, used as fibre basalt and flax, and as a core material is a balsa. Basalt has way better mechanical properties than flax, e-glass, which makes it an interesting material for naval engineers, who can work for lighter and more robust options. Basalt fibre has low water absorption, which is essential in the yacht building sector, and it seems in the yacht industry has shown increased interest in this raw material. Although it is a natural fibre, the utilizing has the same problems as with e-glass. The other proposed material is flax, which is attractive natural fibre reinforcement because it is easy to

handle, has good mechanical properties, good change of bonding with other polymer matrices, extraordinarily light and high aspect ratio as other conventional fibres. It grows fast and raw material is growing in Europe, which makes it easier to obtain later. The core material has proposed balsa, which is a product from the lightest tree. Balsa lightness is caused by the speed of growth of the tree. Balsa wood is a very lightweight material, for that reason, it has been used in many sectors. The using natural fibres there might be an issue with the variability in material quality and the availability of different densities of materials on the market.

The cost and effect of making yacht as an eco-friendly material were evaluated that making yacht from suitable materials has some cases a positive effect on price, but in other cases a negative effect on price. The conventional materials like aluminum and balsa have a positive effect on the price by reducing the total cost of the boat. Unfortunately, other natural fibers have a negative effect on the total price of the sailboat, where flax and basalt increased the total cost. Natural fibers are quite expensive materials. However, the cost of this material is a small part of the total cost of the sailboat. It allows having a creative approach of the material section or marketing point of view, to introduce the new product as a sustainable sailboat. The usage of more natural fibers could be compensated by EU/national policies, when the customers and the manufacturers will strive for it more.

Using natural materials creates a certain contradiction. E-glass fibers as a material are designed to last. There are still GRP sailboats, which are 40-50 years old and sailing still on the seas. On the other hand, natural fibers should be environmentally friendly for decay and probably should not last as glass fibre last. The yacht builders considering the natural fiber as a high risk, because using the conventional e-glass, the manufacturers can give a greater guarantee, that product will last long, with less risk of moisture damage, delamination of fiber and less concern of natural material durability in corrosion environment. It may be one of the biggest obstacles not voluntarily to use natural fibers. The other issue using natural fibers will be related to sustainable engineering and material availability, which allow switching materials or having an option to use different density fibers or sustainably mixing different fibers.

By increasing the natural fiber usage, future, there should be investigate the durability of those fibers, especially flax or other similar fibers, for reducing doubts about that material. The other focus, should be on bio-gradable resins in marine industry, but there are still lack of information about that.

KOKKUVÕTE

Paadiehitustööstus on viimastel aastakümnetel muutunud palju, seda on mõjutanud uued sünteetilised materjalid, näiteks erinevad komposiitmaterjalid. Nende kasutamine on suurenenud märkimisväärselt paadiehituses seetõttu, kuna tegemist on vastupidava, hea töödeldavuse ja kulude osas optimaalsema valikuga. Kompostiitmaterjalid on vastupidavad ultraviolettkiirgusele, mereveele, väsimuskoormustele ning lisaks sellele ka hea tugevuse ja kaalu suhtega, mis muudab need toote jaoks täiuslikuks materjaliks merendussektoris. Sünteetilise materjalide vastupidavus on põhjustanud olukorra, kui paadid jõuavad kasuliku eluea lõppu hilisemal ajal ja neid tuleb hakata utiliseerima. Paraku pole probleemi jäätmekäituse seisukohast hinnatud ega olda teadlikud, mida teha nende purjekatega, mille eluiga on lõppenud ning millega enam merele ei minda. Euroopas on umbes 6 miljonit alust, mis tuleb ühel päeval utiliseerida võimalikult loodust säästval viisil. Väikese keskkonnamõju seisukohast on teised sektorid astunud progressiivsemaid samme, kui on seda merendussektor, näiteks autotööstus on arengult kaugel ees.

Lõputöö keskendub 37-jalase purjeka tootmisele ja parendamisele, et muuta see keskkonnasõbralikumaks ning kui paat jõuab oma kasuliku eluea lõppu, siis utiliseerimise mõju oleks keskkonnale võimalikult väike. Lisaks hinnatakse, kuidas keskkonnasõbalikuks muutumine mõjutab paadi kogumaksumust ja turu konkurentsivõime muutust.

Lahendusi, mis muudavad jahtide ehitamise jätkusuutlikumaks ja keskkonnasõbralikumaks on mitu. Erinevad materjalitootjad üritavad suurendada toodete keskkonnasõbralikkust ja tuua turule uusi keskkonnasõbralikke tooteid. Purjekate tootmises on looduslike komposiitmaterjalide turule tulek tekitanud teatavad huvi kasvu, kus tootjad on teinud suuri pingutusi teadus- ja arendustegevuseks, et parendada looduslike materjalide füüsikalisi omadusi. Üha enam leidub projekte, kus kasutatakse looduslikke komposiitmaterjale, kuid kahjuks seni ainult prototüübi tasandil. Looduslike materjalide kasutamise kohta pole laialdast teavet ega kirjandust, milline on olnud prototüüpide edu või tagasilöögid seonduvalt tootmisega.

Uurimise käigus leiti, et mõistlik oleks kasutada loodussõbaliku materjalina basalti ja linakiud, tuummaterjalina balsat. Basalt on palju paremate mehaaniliste omadustega kui lina-kiudriie ja e-klaas kiudriie, mis muudab selle kasutamise huvitavaks inseneridele, kes saavad töötada kergemate ja tugevamate võimaluste nimel. Basalt-kiul on madal veeimavus võime, mis on oluline purjekate ehitus-valdkonnas ning jahtide tööstuses näib olevat suurenenud huvi selle tooraine vastu. Ehkki basalti näol on tegemist loodusliku kiuga, on selle kasutamisel samad probleemid kui e-klaasi puhul. Teine pakutud materjal on linakiud materjal, mis on looduslike kiudude hulgas üks tugevamaid. Lisaks on seda kerge käsitseda, sellel on head mehaanilised omadused võrreldes teiste polümeeridega, eriti hea on näitaja kaalu ja tugevuse suhtarvudega. Lisaks kasvab lina ise suhteliselt kiiresti ning on kättesaadav ka Euroopas, mis lühendab tarneaegu. Tuummaterjalina on välja pakutud balsa, mis on kõige kergema puu toode, mis turul saadaval. Balsa kerguse taga peitub puu kiire kasv, ning oma kerguse tõttu kasutatakse seda paljudes sektorites. Paraku võib erinevate kiudude kasutamine kaasa tuua probleeme materjalide kvaliteedi varieeruvuse ning erineva tihedusega materjalide saadavuses turul.

Kui hinnata jahi valmistamise keskkonnasõbralike materjalide kulude mõju, siis purjeka valmistamine loodussõbralikest materjalidest omab mõnel juhul positiivset, teisel juhul negatiivset mõju hinnale. Tavalised materjalid nagu alumiinium ja balsa mõjutavad kulude vähenemisena kogumaksumust. Kahjuks mõjuvad teised looduslikud kiud purjeka hinnale negatiivselt, nimelt lina- ja basaltkiud suurendasid kogumaksumust. Looduslikud kiud-materjalid on üsna kallid, kuid siiski nende materjalide osamaksumus moodustab siiski väikese osa purjeka kogukuludest. See võimaldab tootjatel loovat lähenemist materjali kasutamisel või turunduse seisukohast tutvustada uute lahendustega toodet. Lisaks tasuks looduslike materjalide kasutamist vaadata Euroopa Liidu liikmesriikide tasandilt ning toetata seda.

Looduslike materjalide kasutamine tekitab teatud vastuolu. E-klaas on materjal, mis on loodud kestma, sest leidub 40–50-aastaseid klaasplast purjekaid, mis seilavad endiselt meredel. Teisest küljest peaksid looduslikud kiud olema keskkonnasõbralikult ning kergemini lagunema ja tõenäoliselt ei tohiks need kesta nii kaua, kui klaaskiud kestab. Tõenäoliselt peavad purjekate ehitajad looduslikest kiududest ehitatud tooteid vähe kestvateks, ning tavalise e-klaasi kasutamisel saavad nad anda suurema garantii ja kindlustunde, et toode kestab kauem ning on vähem vastuvõtlik niiskuskahjustustele. See võib olla üks suurimaid takistusi, mis pärsib looduslike kiudude vabatahtlikku kasutamist purjejahi tootjate poolt. Teine looduslikku kiu kasutamisega seonduv küsimus on seotud ka jätkusuutliku inseneeriaga ja materjalide kättesaadavusega. See võimaldab materjalide vahetamist või võimalust kasutada erinevaid komposiite omavahel.

Looduslike komposiitmaterjalide kasutuse suurendamiseks tuleks tulevikus uurida, eriti lina või teiste sarnaste kiudude vastupidavust, et vähendada kahtlusi selle materjali kasutamist purjejahi töötajate silmis. Lisaks on vähe informatsiooni looduslike ja loodusõbralike vaikude kasutamisest merenduses, see on samuti põnev teema, mida tasuks tulevikus uurida.

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APPENDICES

Appendix 1. Current deck layup schema of the boat

Deck Layup 37 ft. Yacht			**Infusion - Female mould**			**Resin Vinilester**		**Deck total surfce = 43 m2**				
Description	**Layer**	**Material**	**Reinforcment weight** [g/m2]	**Fiber orientation reffered to CL**	**N° of layers**	**Fiber Cont.** % in	**Lam. weight unit.** [kg/m2]	**Lamination area** [m2]	**Lam. Weight tot.** kg	**Partial**	**Resin** kg	**Partial**
Skin coat	0	Gel Coat	1200		1	100%	0,96		41,3			
	1	CSM 300	300	/	1	30%	1,00	44,7	44,7	**93**	31,3	**36**
	3	CSM 225	225	/	1	30%	0,75	9,0	6,8		4,8	
Outer Skin	4	E-WR 300	300	0-90°	1	60%	0,50	44,7	26,1		10,4	
	5	E-UD 300	300	0	2	60%	0,50	31,6	15,8		6,3	
	6	E-UD 300	300	90	2	60%	0,50	15,2	7,6	**76**	3,0	**30**
	7	E-DB 300	300	+-45°	1	60%	0,50	44,7	22,4		8,9	
	8	E-DB 300	300	+-45°	3	60%	0,50	15,6	7,8		3,1	
Resin	Resin uptake						1,50	43,0	64,5		64,5	
Core	PVC	PVC75/ 20mm					1,50	40,0	60,0	**135**	0,0	**65**
	PVC	PVC 200/Marine Plywood 20mm					10,00	1,0	10,0		0,0	
	Solid	QX E 1200	1200		2	60%	2,00	4,2	8,3	**8**	3,3	**3**
Inner Skin	9	E-DB 300	300	+-45°	3	60%	0,50	15,6	7,8		3,1	
	10	E-DB 300	300	+-45°	1	60%	0,50	44,7	22,4		8,9	
	11	E-UD 300	300	90	2	60%	0,50	15,2	7,6	**76**	3,0	**30**
	12	E-UD 300	300	0	2	60%	0,50	31,6	15,8		6,3	
	13	E-WR 300	300	0-90°	1	60%	0,50	44,7	22,4		8,9	
						Unit. Weight =	**6,96**	**total weight**	**396**		**173**	

Appendix 2. Current layup of the hull

Hull Layup 37 ft.				**Infusion - > Female mould**			**Resin Vinilester**			**Hull total surface = 56 m^2**			
Description	**Layer**	**Material**	**Reinforcment weight** [g/m2]	**roll width** [m]	**Fiber orientation reffered to CL**	**N° of layers**	**Fiber Cont.** % in	**Lam. weight unit.** [kg/m2]	**Lamination area** [m2]	**Lam. Weight tot.** kg	**Partial**	**Resin** kg	**Partial**
Skin coat	0	Vinilester Paint	1000			1		0,70		39,2	**39**		**39**
Outer Skin	1	E-UD 300	300	0,5	90°	1	60%	0,50	57,1	28,6		11,4	
	2	E-UD 300	300	0,5	0°	1	60%	0,50	57,1	28,6		11,4	
	3	E-UD 300	300	0,5	90°	1	60%	0,50	37,4	18,7		7,5	
	4	E-UD 300	300	0,5	0°	3	60%	0,50	90,0	45,0	**180**	18,0	**72**
	5	E-UD 300	300	0,5	90°	2	60%	0,50	22,0	11,0		4,4	
	6	E-DB 400	400	1,25	+-45°	1	60%	0,67	58,2	38,8		15,5	
	7	E-DB 400	400	1,25	+-45°	2	60%	0,67	14,6	9,7		3,9	
Resin								1,50	56,0	84,0		84,0	
Core	PVC	PVC75 / 20mm						1,50	45,0	67,5	**178**		**84**
	PVC	PVC130 / 20mm						2,60	10,0	26,0			
	Single skin	QX E 1200	1200	1,25	+-45°	10	60%	2,00	27,0	54,1	**54**	21,6	**22**
Inner Skin	8	E-DB 400	400	1,25	+-45°	2	60%	0,67	14,6	9,7		3,9	
	9	E-DB 400	400	1,25	+-45°	1	60%	0,67	58,2	38,8		15,5	
	10	E-UD 300	300	0,5	90°	2	60%	0,50	22,0	11,0		4,4	
	11	E-UD 300	300	0,5	0°	3	60%	0,50	90,0	45,0	**180**	18,0	**72**
	12	E-UD 300	300	0,5	90°	1	60%	0,50	37,4	18,7		7,5	
	13	E-UD 300	300	0,5	0°	1	60%	0,50	57,1	28,6		11,4	
	14	E-UD 300	300	0,5	C	1	60%	0,50	57,1	28,6		11,4	
						Unit. Weight =		**5,53**	**total weight**	**637**		**250**	

Appendix 3. Current layup of bow horizontal and vertical panels

Bow horizontal panels

Description	Layer	Material	Reinforcment weight [g/m2]	Fiber orientation reffered to CL	N° of layers	Fiber Cont. %	Lam. weight unit. [kg/m2]	Lamination area [m2]	Lam. Weight tot. kg	Partial	Resin kg	Partial
Outer Skin	1	E-DB 400	400	+-45°	1	50%	0,80	1,3	1,0	3	0,5	2
	2	E-WR 400	400	0°-90°	1	50%	0,80	1,3	1,0		0,5	
	3	E-DB 400	400	+-45°	1	50%	0,80	1,3	1,0		0,5	
	4	E-UD 300	300	0°	1	50%	0,60	0,5	0,3		0,1	
Resin	Resin uptake						1,50	0,2	0,3	8	0,3	0
Core	PVC	PVC75 / 15mm					1,50	0,2	0,3			
	PVC	PLYWOOD 15mm					7,20	1,1	7,6			
	CAPPING	E-UD 300	300	0°	6	50%	0,60	3,3	2,0	2	1,0	1
Inner Skin	5	E-UD 300	300	0°	1	50%	0,60	0,5	0,3	2	0,1	1
	6	E-DB 400	400	+-45°	1	50%	0,80	1,3	1,0		0,5	
	7	E-WR 400	400	0°-90°	1	50%	0,80	1,3	1,0		0,5	
					Unit. Weight =		**4,50**	**total weight =**	**16**		**4**	

Bow vertical Panels

Description	Layer	Material	Reinforcment weight [g/m2]	Fiber orientation reffered to CL	N° of layers	Fiber Cont. %	Lam. weight unit. [kg/m2]	Lamination area [m2]	Lam. Weight tot. kg	Partial	Resin kg	Partial
Outer Skin	1	E-WR 400	400	0°-90°	1	50%	0,80	0,7	0,6	2	0,3	1
	2	E-DB 400	400	+-45°	1	50%	0,80	1,3	1,0		0,5	
Resin	Resin uptake						1,50	0,7	1,0	2	1,0	1
Core	PVC	PVC75 / 15mm					1,50	0,7	1,0			
	PVC	PLYWOOD 15mm					7,20	0,0	0,3			
	CAPPING	E-UD 300	300	0°	6	50%	0,60	1,2	0,7	1	0,4	0
Inner Skin	3	E-DB 400	400	+-45°	1	50%	0,80	0,7	0,6	1	0,3	1
	4	E-WR 400	400	0°-90°	1	50%	0,80	0,7	0,6		0,3	
					Unit. Weight =		**4,70**	**total weight =**	**6**		**3**	

Appendix 4. Lay-up of forepeak bulkhead and vertical panels

Forepeak bulkhead

Description	Layer	Material	Reinforcment weight [g/m2]	Fiber orientation reffered to CL	N° of layers	Fiber Cont. %	Lam. weight unit. [kg/m2]	Lamination area [m2]	Lam. Weight tot. kg	Partial	Resin kg	Partial
Outer Skin	1	E-DB 400	400	+-45°	1	50%	0,80	0,4	0,3		0,2	
	2	E-DB 400	400	+-45°	3	50%	0,80	2,5	2,0	3	1,0	1
	3	E-UD 300	300	0°	1	50%	0,60	0,5	0,3		0,2	
Resin	Resin uptake						1,50	0,8	1,2	2	1,2	1
Core	PVC	PVC75 / 15mm					1,50	0,8	1,2			
	CAPPING	E-UD 300	300	0°	6	50%	0,60	3,0	1,8	2	0,9	1
Inner Skin	4	E-UD 300	300	0°	1	50%	0,60	0,5	0,3		0,2	
	5	E-DB 400	400	+-45°	3	50%	0,80	2,5	2,0	3	1,0	1
	6	E-DB 400	400	+-45°	1	50%	0,80	0,4	0,3		0,2	
					Unit. Weight =		**4,30**	**total weight =**	**10**		**5**	

Vertical panels

Description	Layer	Material	Reinforcment weight [g/m2]	Fiber orientation reffered to CL	N° of layers	Fiber Cont. %	Lam. weight unit. [kg/m2]	Lamination area [m2]	Lam. Weight tot. kg	Partial	Resin kg	Partial
Outer Skin	1	E-DB 400	400	+-45°	1	50%	0,80	0,2	0,1	1	0,1	0,3
	2	E-DB 400	400	+-45°	3	50%	0,80	0,5	0,4		0,2	
Resin	Resin uptake						1,50	0,2	0,3	1	0,3	0,3
Core	PVC	PVC75 / 15mm					1,50	0,2	0,3			
	CAPPING	E-UD 300	300	0°	6	50%	0,60	1,4	0,8	1	0,4	##
	5	E-DB 400	400	+-45°	3	50%	0,80	0,5	0,4		0,2	
	6	E-DB 400	400	+-45°	1	50%	0,80	0,2	0,1		0,1	
					Unit. Weight =		**6,30**	**total weight =**	**2**		**1**	

Appendix 5. Current lay-up of vertical panels in the middle section and stern panels

Vertical panels in mid. section												
Description	**Layer**	**Material**	**Reinforcment weight**	**Fiber orientation reffered to CL**	**N° of layers**	**Fiber Cont.**	**Lam. weight unit.**	**Lamination area**	**Lam. Weight tot.**	**Partial**	**Resin**	**Partial**
			[g/m2]			%	[kg/m2]	[m2]	kg		kg	
Outer Skin	1	E-DB 400	400	+-45°	1	50%	0,80	0,3	0,2		0,1	
	2	E-DB 400	400	+-45°	3	50%	0,80	3,2	2,6	**3**	1,3	**2**
	3	E-UD 300	300	0°	1	50%	0,60	0,7	0,4		0,2	
Resin	Resin uptake						1,50	1,0	1,5	**3**	1,5	**2**
Core	PVC	PVC75 / 15mm					1,50	1,0	1,5			
	CAPPING	E-UD 300	300	0°	6	50%	0,60	3,8	2,3	**2**	1,1	**1**
Inner Skin	4	E-UD 300	300	0°	1	50%	0,60	0,7	0,4		0,2	
	5	E-DB 400	400	+-45°	3	50%	0,80	3,2	2,6	**3**	1,3	**2**
	6	E-DB 400	400	+-45°	1	50%	0,80	0,3	0,2		0,1	
					Unit. Weight =		**6,30**	**total weight =**	**12**		**6**	

Stren panels												
Description	**Layer**	**Material**	**Reinforcment weight**	**Fiber orientation reffered to CL**	**N° of layers**	**Fiber Cont.**	**Lam. weight unit.**	**Lamination area**	**Lam. Weight tot.**	**Partial**	**Resin**	**Partial**
			[g/m2]			%	[kg/m2]	[m2]	kg		kg	
Outer Skin	1	E-DB 400	400	+-45°	1	50%	0,80	1,8	1,5		0,7	
	2	E-WR 400	400	0°-90°	1	50%	0,80	1,8	1,5	**5**	0,7	**2**
	3	E-DB 400	400	+-45°	1	50%	0,80	1,8	1,5		0,7	
	4	E-UD 300	300	0°	1	50%	0,60	1,0	0,6		0,3	
Resin	Resin uptake						1,50	1,8	2,6	**4**	2,6	**3**
Core	PVC	PVC75 / 15mm					1,50	0,6	1,0			
	CAPPING	E-UD 300	300	0°	6	50%	0,60	3,3	2,0	**2**	1,0	**1**
Inner Skin	5	E-UD 300	300	0°	1	50%	0,60	1,0	0,6		0,3	
	6	E-DB 400	400	+-45°	1	50%	0,80	1,8	1,5	**3**	0,7	**2**
	7	E-WR 400	400	0°-90°	1	50%	0,80	1,8	1,5		0,7	
					Unit. Weight =		**4,50**	**total weight =**	**14**		**8**	

Appendix 6. New deck lay-up with flax

Deck Layup 37 ft. Yacht		**Infusion - Female mould**		**ONE High Biobased Laminating Epoxy**					**Deck total surfce = 43 m2**			
Description	**Layer**	**Material**	**Reinforcment weight**	**Fiber orientation reffered to CL**	**N° of layers**	**Fiber Cont.**	**Lam. weight unit.**	**Lamination area**	**Lam. Weight tot.**	**Partial**	**Resin**	**Partial**
			[g/m2]			%	[kg/m2]	[m2]	kg		kg	
	0	Gel Coat	1200		1	100%	1,0		41,3			
Skin coat	1	ampliTex 5025 UD	300	/	1	30%	1,0	44,7	44,7	**97**	31,3	**39**
	3	ampliTex 5025 UD	300	/	1	30%	1,2	9,0	10,5		7,4	
	4	ampliTex 5040 twill WR	300	0-90°	1	50%	0,6	44,7	26,8		13,4	
	5	ampliTex 5008 DB	350	0	3	50%	0,6	47,4	28,4		14,2	
Outer Skin	6	ampliTex 5008 DB	350	90	3	50%	0,6	22,8	13,7	**111**	6,8	**56**
	7	ampliTex 5025 DB	300	+-45°	1	50%	0,7	44,7	31,3		15,6	
	8	ampliTex 5025 UD	300	+-45°	3	50%	0,7	15,6	10,9		5,5	
Resin	Resin uptake						1,5	43,0	64,5		64,5	
	Balsa	Balsa SBC.50 19mm					2,1	40,0	82,8	**150**	0,0	**65**
Core	Balsa	Balsa SBC.100 19mm					2,8	1,0	2,8		0,0	
	Solid	ampliTex 5025 DB	300	+-45°	7	50%	0,7	14,6	10,2	**10**	5,1	**5**
	9	ampliTex 5025 DB	300	+-45°	3	50%	0,7	15,6	10,9		5,5	
	10	ampliTex 5025 DB	300	+-45°	1	50%	0,7	44,7	31,3		15,6	
Inner Skin	11	ampliTex 5008 UB	350	90	3	50%	0,6	22,8	13,7	**111**	6,8	**56**
	12	ampliTex 5008 UB	350	0	3	50%	0,6	47,4	28,4		14,2	
	13	ampliTex 5040 twill	300	0-90°	1	50%	0,6	45,2	27,1		13,5	
				Unit. Weight =		**7,86**		**total weight =**	**479**		**220**	

Appendix 7. New deck lay-up with Basalt

Deck Layup 37 ft. Yacht			**Infusion - Female mould**			**ONE High Biobased Laminating Epoxy**				**Deck total surfce = 43 m2**		
Description	**Layer**	**Material**	**Reinforcment** [g/m2]	**Fiber orientation reffered to CL**	**N° of layers**	**Fiber Cont.** %	**Lam. weight** [kg/m2]	**Lamination area** [m2]	**Lam. Weight tot.** kg	**Partial**	**Resin** kg	**Partial**
Skin coat	0	Gel Coat	1200		1	100%	0,96		41,3	**108**		**47**
	1	Basalt DB450	450	/	1	30%	1,00	44,7	67,0		46,9	
	4	Basalt WR350	350	0-90°	1	60%	0,58	44,7	26,1		10,4	
Outer Skin	5	Basalt UD350	350	0	2	60%	0,58	31,6	9,2	**83**	3,7	**33**
	6	Basalt UD350	350	90	2	60%	0,58	15,2	8,9		3,5	
	7	Basalt DB450	450	+-45°	1	60%	0,75	44,7	33,5		13,4	
	8	Basalt DB600	600	+-45°	1	60%	1,00	5,2	5,2		2,1	
	Resin uptake						1,50	43,0	64,5		64,5	
Resin	Balsa	Balsa SBC.50 19mm					2,07	40,0	82,8	**150**	0,0	**65**
Core	Balsa	Balsa SBC.100 19mm					2,82	1,0	2,8		0,0	
	Solid	Basalt QUADRI	1000'		2	60%	4,00	4,2	6,9		2,8	
	9	Basalt DB600	600	+-45°	1	60%	1,00	5,2	5,2	**7**	2,1	**3**
Inner Skin	10	Basalt DB450	450	+-45°	1	60%	0,75	44,7	33,5	**83**	13,4	**33**
	11	Basalt UD350	350	90	2	60%	0,58	15,2	8,9		3,5	
	12	Basalt UD350	350	0	2	60%	0,58	31,6	9,2		3,7	
	13	Basalt WR350	350	0-90°	1	60%	0,58	44,7	26,1		10,4	
					Unit. Weight =		**8,20**	**total weight =**	**431**		**180**	

Appendix 8. New hull lay-up with flax

Hull Layup 37 ft.				**Infusion - >Male mould**			**ONE High Biobased Laminating Epoxy**			**Hull total surface = 56 m^2**		
Description	**Layer**	**Material**	**Reinforcment weight** [g/m2]	**Fiber orientation reffered to CL**	**N° of layers**	**Fiber Cont** %	**Lam. weight unit.** [kg/m2]	**Lamination area** [m2]	**Lam. Weight tot.** kg	**Partial**	**Resin** kg	**Partial**
Skin coat	0	Vinilester Base & Paint	1000		1		0,70		39,2	**39**		**39**
Outer Skin	1	ampliTex 5025 UD300	300	90°	1	50%	0,50	56,4	33,9		16,9	
	2	ampliTex 5025 UD300	300	0°	1	50%	0,50	56,4	33,9		16,9	
	3	ampliTex 5025 UD300	300	90°	1	50%	0,50	37,0	22,2		11,1	
	4	ampliTex 5025 UD300	300	0°	4	50%	0,50	120,0	72,0	**233**	36,0	**116**
	5	ampliTex 5025 UD300	300	90°	3	50%	0,50	33,0	19,8		9,9	
	6	ampliTex5008 DB 350	350	+-45°	1	50%	0,58	58,2	40,7		20,4	
	7	ampliTex5008 DB 350	350	+-45°	2	50%	0,58	14,6	10,2		5,1	
Resin	Resin uptake						1,50	56,0	84,0	**198**	84,0	**84**
Core	Balsa	Balsa 19mm SCB					2,07	55,0	113,9		0,0	
	Single skin	ampliTex5008 DB 350	350	+-45°	35	50%	2,00	94,6	66,2	**66**	33,1	**33**
Inner Skin	8	ampliTex5008 DB 350	350	+-45°	2	50%	0,58	14,6	10,2		5,1	
	9	ampliTex5008 DB 350	350	+-45°	1	50%	0,58	58,2	40,7		20,4	
	10	ampliTex 5025 UD300	300	90°	3	50%	0,50	33,0	19,8		9,9	
	11	ampliTex 5025 UD300	300	0°	4	50%	0,50	120,0	72,0	**233**	36,0	**116**
	12	ampliTex 5025 UD300	300	90°	1	50%	0,50	37,0	22,2		11,1	
	13	ampliTex 5025 UD300	300	0°	1	50%	0,50	56,4	33,9		16,9	
	14	ampliTex 5025 UD300	300	90°	1	50%	0,50	56,4	33,9		16,9	
					Unit. Weight =		**6,57**	**total weight =**	**769**		**350**	

Appendix 9. New hull lay-up with basalt

Hull Layup 37 ft.				Infusion - >Male mould			ONE High Biobased Laminating Epoxy			Hull total surface = 56 m^2		
Description	**Layer**	**Material**	**Reinforcment weight** [g/m2]	**Fiber orientation reffered to CL**	**N° of layers**	**Fiber Cont** %	**Lam. weight unit.** [kg/m2]	**Lamination area** [m2]	**Lam. Weight tot.** kg	**Partial**	**Resin** kg	**Partial**
Skin coat	0	Vinilester Base & Paint	1000		1		0,70		39,2	**39**		**39**
Outer Skin	1	Basalt UD350	350	90°	1	60%	0,58	56,4	32,9	**184**	13,2	**74**
	2	Basalt UD350	350	0°	1	60%	0,58	56,4	32,9		13,2	
	3	Basalt UD350	350	90°	1	60%	0,58	37,0	21,6		8,6	
	4	Basalt UD350	350	0°	2	60%	0,58	60,0	35,0		14,0	
	5	Basalt UD350	350	90°	2	60%	0,58	22,0	12,8		5,1	
	6	Basalt BI450	450	+-45°	1	60%	0,58	58,2	43,7		17,5	
	7	Basalt BI450	450	+-45°	2	60%	0,58	7,3	5,5		2,2	
Resin	Resin uptake						1,50	56,0	84,0	**198**	84,0	**84**
Core	Balsa	Balsa 19mm SCB					2,07	55,0	113,9		0,0	
	Single skin	Basalt 1000	1000	+-45°	10	60%	2,00	27,0	45,0	**45**	18,0	**18**
Inner Skin	8	Basalt BI450	450	+-45°	2	60%	0,58	7,3	5,5	**184**	2,2	**74**
	9	Basalt BI450	450	+-45°	1	60%	0,58	58,2	43,7		17,5	
	10	Basalt UD350	350	90°	2	60%	0,58	22,0	12,8		5,1	
	11	Basalt UD350	350	0°	2	60%	0,58	60,0	35,0		14,0	
	12	Basalt UD350	350	90°	1	60%	0,58	37,0	21,6		8,6	
	13	Basalt UD350	350	0°	1	60%	0,58	56,4	32,9		13,2	
	14	Basalt UD350	350	90°	1	60%	0,58	56,4	32,9		13,2	
					Unit. Weight =		**6,27**	**total weight =**	**651**		**250**	

Appendix 10. New lay-up of bow horizontal and vertical panels with flax

Bow horizontal panels			Infusion			ONE High Biobased Laminating Epoxy						
Description	**Layer**	**Material**	**Reinforcment weight** [g/m2]	**Fiber orientation reffered to CL**	**N° of layers**	**Fiber Cont.** %	**Lam. weight unit.** [kg/m2]	**Lamination area** [m2]	**Lam. Weight tot.** kg	**Partial**	**Resin** kg	**Partial**
Outer Skin	1	ampliTex 5008 DB	350	+-45°	1	50%	0,70	1,3	0,9	4	0,5	3
	2	ampliTex 5040 twill	350	0°-90°	1	50%	0,70	1,3	0,9		0,5	
	3	ampliTex 5008 DB	350	+-45°	2	50%	0,70	2,6	1,8		0,9	
	4	ampliTex Fusion 5027-4	160	0°	1	50%	0,32	0,9	0,3		0,2	
Resin	Resin uptake						1,50	0,2	0,3	2	0,2	0
Core	Balsa	Balsa SBC 15mm					1,63	1,3	2,1			
	CAPPING	ampliTex Fusion 5027-4	160	0°	12	50%	0,32	6,2	2,0	2	1,0	1
Inner Skin	5	ampliTex Fusion 5027-4	160	0°	1	50%	0,32	0,8	0,3	3	0,1	2
	6	ampliTex 5008 DB	350	+-45°	2	50%	0,70	2,6	1,8		0,9	
	7	ampliTex 5040 twill	350	0°-90°	1	50%	0,70	1,3	0,9		0,9	
								total weight =	**11**		**6**	

Bow vertical Panels												
Description	**Layer**	**Material**	**Reinforcment weight** [g/m2]	**Fiber orientation reffered to CL**	**N° of layers**	**Fiber Cont.** %	**Lam. weight unit.** [kg/m2]	**Lamination area** [m2]	**Lam. Weight tot.** kg	**Partial**	**Resin** kg	**Partial**
Outer Skin	1	ampliTex 5040 twill	350	0°-90°	1	50%	0,70	0,7	0,5	2	0,2	1
	2	ampliTex 5008 DB	350	+-45°	2	50%	0,70	2,6	1,8		0,9	
Resin	Resin uptake						1,50	0,7	1,0	2	1,0	1
Core	Balsa	Balsa SBC 15mm					1,63	0,7	1,1			
	CAPPING	ampliTex Fusion 5027-4	160	0°	12	50%	0,32	2,3	0,7	1	0,4	0
Inner Skin	3	ampliTex 5008 DB	350	+-45°	2	50%	0,70	1,4	1,0	1	0,5	1
	4	ampliTex 5040 twill	350	0°-90°	1	50%	0,70	0,7	0,5		0,2	
								total weight =	**7**		**3**	

Appendix 11. New lay-up of forepeak bulkhead and vertical panels with flax

Forepeak bulkhead			Infusion				ONE High Biobased Laminating Epoxy					
Description	**Layer**	**Material**	**Reinforcement weight** [g/m2]	**Fiber orientation reffered to CL**	**N° of layers**	**Fiber Cont.** %	**Lam. weight unit.** [kg/m2]	**Lamination area** [m2]	**Lam. Weight tot.** kg	**Partial**	**Resin** kg	**Partial**
Outer Skin	1	ampliTex 5008 DB	350	+-45°	1	50%	0,70	0,4	0,3	2	0,1	1
	2	ampliTex 5008 DB	350	+-45°	3	50%	0,70	3,4	2,3		1,2	
	3	ampliTex Fusion 5027-4	160	0°	1	50%	0,32	1,0	0,3		0,2	
Resin	Resin uptake						1,50	0,8	1,2	3	1,2	1
Core	Balsa	Balsa SBC 15mm					1,63	0,8	1,3			
	CAPPING	ampliTex Fusion 5027-4	160	0°	12	50%	0,32	5,6	1,8	2	0,9	1
Inner Skin	4	ampliTex Fusion 5027-4	160	0°	1	50%	0,32	1,0	0,3	3	0,2	2
	5	ampliTex 5008 DB	350	+-45°	3	50%	0,70	3,4	2,3		1,2	
	6	ampliTex 5008 DB	350	+-45°	1	50%	0,70	0,4	0,3		0,1	
							total weight =		**10**		**5**	

Vertical panels												
Description	**Layer**	**Material**	**Reinforcement weight** [g/m2]	**Fiber orientation reffered to CL**	**N° of layers**	**Fiber Cont.** %	**Lam. weight unit.** [kg/m2]	**Lamination area** [m2]	**Lam. Weight tot.** kg	**Partial**	**Resin** kg	**Partial**
Outer Skin	1	ampliTex 5008 DB	350	+-45°	1	50%	0,70	0,2	0,1	1	0,1	0
	2	ampliTex 5008 DB	350	+-45°	3	50%	0,70	0,7	0,5		0,2	
Resin	Resin uptake						1,50	0,2	0,3	1	0,3	0
Core	Balsa	Balsa SBC 15mm					1,63	0,2	0,3		0,0	
	CAPPING	ampliTex Fusion 5027-4	160	0°	12	50%	0,32	2,5	0,8	1	0,4	0
	5	ampliTex 5008 DB	350	+-45°	3	50%	0,70	0,7	0,5		0,2	
	6	ampliTex 5008 DB	350	+-45°	1	50%	0,70	0,2	0,1		0,1	
							total weight=		**3**		**1**	

Appendix 12. New lay-up of vertical panels in the middle section and stern panels with flax

Vertical panels in mid. section						Infusion		ONE High Biobased Laminating Epoxy				
Description	**Layer**	**Material**	**Reinforcement weight** [g/m2]	**Fiber orientation reffered to CL**	**N° of layers**	**Fiber Cont.** %	**Lam. weight unit.** [kg/m2]	**Lamination area** [m2]	**Lam. Weight tot.** kg	**Partial**	**Resin** kg	**Partial**
Outer Skin	1	ampliTex 5008 DB	350	+-45°	1	50%	0,70	0,3	0,2	4	0,1	2
	2	ampliTex 5008 DB	350	+-45°	3	50%	0,70	4,3	3,0		1,5	
	3	ampliTex Fusion 5027-4	160	0°	1	50%	0,32	1,3	0,4		0,2	
Resin	Resin uptake						1,50	1,0	1,5	3	1,5	1
Core	Balsa	Balsa SBC 15mm					1,63	1,0	1,7		0,0	
	CAPPING	ampliTex Fusion 5027-4	160	0°	12	50%	0,32	7,1	2,3	2	1,1	1
Inner Skin	4	ampliTex Fusion 5027-4	160	0°	1	50%	0,32	1,3	0,4	4	0,2	3
	5	ampliTex 5008 DB	350	+-45°	3	50%	0,70	4,3	3,0		1,5	
	6	ampliTex 5008 DB	350	+-45°	1	50%	0,70	0,3	0,2		0,1	
							total weight=		**13**		**6**	
Stren panels												
Description	**Layer**	**Material**	**Reinforcement weight** [g/m2]	**Fiber orientation reffered to CL**	**N° of layers**	**Fiber Cont.** %	**Lam. weight unit.** [kg/m2]	**Lamination area** [m2]	**Lam. Weight tot.** kg	**Partial**	**Resin** kg	**Partial**
Outer Skin	1	ampliTex 5008 DB	350	+-45°	1	50%	0,70	1,8	1,3	6	0,6	3
	2	ampliTex 5040 twill	350	0°-90°	1	50%	0,70	1,8	1,3		0,6	
	3	ampliTex 5008 DB	400	+-45°	2	50%	0,80	3,6	2,9		1,5	
	4	ampliTex Fusion 5027-4	150	0°	2	50%	0,30	1,8	0,5		0,3	
Resin	Resin uptake						1,50	1,8	2,6	4	2,6	3
Core	Balsa	Balsa SBC 15mm					1,63	0,6	1,0			
	CAPPING	ampliTex Fusion 5027-4	160	0°	12	50%	0,32	6,2	2,0	2	1,0	1
Inner Skin	5	ampliTex Fusion 5027-4	160	0°	2	50%	0,32	1,8	0,6	4	0,3	2
	6	ampliTex 5008 DB	350	+-45°	2	50%	0,70	3,6	2,6		1,3	
	7	ampliTex 5040 twill	350	0°-90°	1	50%	0,70	1,8	1,3		0,6	
							total weight =		**16**		**9**	

Appendix 13. New lay-up of bow horizontal and vertical panels with basalt

Bow horizontal panels			**Infusion**					**ONE High Biobased Laminating Epoxy**				
Description	**Layer**	**Material**	**Reinforcment weight**	**Fiber orientation reffered to CL**	**N° of layers**	**Fiber Cont.**	**Lam. weight unit.**	**Lamination area**	**Lam. Weight tot.**	**Partial**	**Resin**	**Partial**
			[g/m2]			%	[kg/m2]	[m2]	kg		kg	
Outer Skin	1	Basalt DB 450	450	+-45°	1	50%	0,90	1,3	1,2	**4**	0,6	**2**
	2	Basalt WR 350	350	0°-90°	1	50%	0,70	1,3	0,9		0,4	
	3	Basalt DB 450	450	+-45°	1	50%	0,90	1,3	1,2		0,6	
	4	Basalt UD 350	350	0°	1	50%	0,70	0,5	0,3		0,2	
Resin	Resin uptake						1,50	0,2	0,3	**2**	0,3	**0**
Core	Balsa	Balsa SBC 15mm					1,63	1,3	2,1			
	CAPPING	Basalt UD 350	350	0°	4	50%	0,70	2,2	1,5	**2**	1,2	**1**
Inner Skin	5	Basalt UD 350	350	0°	1	50%	0,70	0,5	0,3	**2**	0,2	**1**
	6	Basalt DB 450	450	+-45°	1	50%	0,90	1,3	1,2		0,6	
	7	Basalt WR 350	350	0°-90°	1	50%	0,70	1,3	0,9		0,4	
							total weight =		**10**		**4**	

Bow vertical Panels												
Description	**Layer**	**Material**	**Reinforcment weight**	**Fiber orientation reffered to CL**	**N° of layers**	**Fiber Cont.**	**Lam. weight unit.**	**Lamination area**	**Lam. Weight tot.**	**Partial**	**Resin**	**Partial**
			[g/m2]			%	[kg/m2]	[m2]	kg		kg	
Outer Skin	1	Basalt WR 350	350	0°-90°	1	50%	0,70	0,7	0,5	**2**	0,2	**1**
	2	Basalt DB 450	450	+-45°	1	50%	0,90	1,3	1,2		0,6	
Resin	Resin uptake						1,50	0,7	1,0	**2**	1,0	**1**
Core	Balsa	Balsa SBC 15mm					1,63	0,7	1,1			
	CAPPING	Basalt UD 350	350	0°	4	50%	0,70	0,8	0,6	**1**	0,3	**0**
Inner Skin	3	Basalt DB 450	450	+-45°	1	50%	0,90	0,7	0,6	**1**	0,3	**1**
	4	Basalt WR 350	350	0°-90°	1	50%	0,70	0,7	0,5		0,2	
							total weight =		**6**		**3**	

Appendix 14. New lay-up of forepeak bulkhead and vertical panels with basalt

Forepeak bulkhead						Infusion		ONE High Biobased Laminating Epoxy				
Description	**Layer**	**Material**	**Reinforcement weight** [g/m2]	**Fiber orientation reffered to CL**	**N° of layers**	**Fiber Cont.** %	**Lam. weight unit.** [kg/m2]	**Lamination area** [m2]	**Lam. Weight tot.** kg	**Partial**	**Resin** kg	**Partial**
Outer Skin	1	Basalt DB 450	450	+-45°	1	50%	0,90	0,4	0,4	**3**	0,2	**1**
	2	Basalt DB 600	600	+-45°	2	50%	1,20	1,7	2,0		1,0	
	3	Basalt UD 350	350	0°	1	50%	0,70	0,5	0,4		0,2	
Resin	Resin uptake						1,50	0,8	1,2	**3**	1,2	**1**
Core	Balsa	Balsa SBC 15mm					1,63	0,8	1,3			
	CAPPING	Basalt UD 350	350	0°	4	50%	0,70	2,0	1,4	**1**	1,1	**1**
Inner Skin	4	Basalt UD 350	350	0°	1	50%	0,70	0,5	0,4	**3**	0,2	**1**
	5	Basalt DB 600	600	+-45°	2	50%	1,20	1,7	2,0		1,0	
	6	Basalt DB 450	450	+-45°	1	50%	0,90	0,4	0,4		0,2	
							total weight =		**9**		**4**	

Vertical panels												
Description	**Layer**	**Material**	**Reinforcement weight** [g/m2]	**Fiber orientation reffered to CL**	**N° of layers**	**Fiber Cont.** %	**Lam. weight unit.** [kg/m2]	**Lamination area** [m2]	**Lam. Weight tot.** kg	**Partial**	**Resin** kg	**Partial**
Outer Skin	1	Basalt DB 450	450	+-45°	1	50%	0,90	0,2	0,2	**1**	0,1	**0**
	2	Basalt DB 600	600	+-45°	2	50%	1,20	0,4	0,4		0,2	
Resin	Resin uptake						1,50	0,2	0,3	**1**	0,3	**0**
Core	Balsa	Balsa SBC 15mm					1,63	0,2	0,3			
	CAPPING	Basalt UD 350	350	0°	4	50%	0,70	0,9	0,6	**1**	0,5	**0**
	5	Basalt DB 600	600	+-45°	2	50%	1,20	0,4	0,4		0,2	
	6	Basalt DB 450	450	+-45°	1	50%	0,90	0,2	0,2		0,1	
							total weight =		**3**		**1**	

Appendix 15. New lay-up of vertical panels in the middle section and stern panels with basalt

Vertical panels in mid. section					Infusion			ONE High Biobased Laminating Epoxy				
Description	**Layer**	**Material**	**Reinforcment weight** [g/m2]	**Fiber orientation reffered to CL**	**N° of layers**	**Fiber Cont.** %	**Lam. weight unit.** [kg/m2]	**Lamination area** [m2]	**Lam. Weight tot.** kg	**Partial**	**Resin** kg	**Partial**
	1	Basalt DB 450	450	+-45°	1	50%	0,90	0,3	0,2		0,1	
Outer Skin	2	Basalt DB 600	600	+-45°	2	50%	1,20	2,1	2,6	**3**	1,3	**2**
	3	Basalt UD 350	350	0°	1	50%	0,70	0,7	0,5		0,2	
Resin	Resin uptake						1,50	1,0	1,5	**3**	1,5	**2**
Core	Balsa	Balsa SBC 15mm					1,63	1,0	1,7			
	CAPPING	Basalt UD 350	350	0°	4	50%	0,70	2,5	1,8	**2**	1,3	**1**
	4	Basalt UD 350	350	0°	1	50%	0,70	0,7	0,5		0,2	
Inner Skin	5	Basalt DB 600	600	+-45°	2	50%	1,20	2,1	2,6	**3**	1,3	**2**
	6	Basalt DB 450	450	+-45°	1	50%	0,90	0,3	0,2		0,1	
							total weight =		**12**		**6**	
Stren panels												
Description	**Layer**	**Material**	**Reinforcment weight** [g/m2]	**Fiber orientation reffered to CL**	**N° of layers**	**Fiber Cont.** %	**Lam. weight unit.** [kg/m2]	**Lamination area** [m2]	**Lam. Weight tot.** kg	**Partial**	**Resin** kg	**Partial**
	1	Basalt DB 450	450	+-45°	1	50%	0,90	1,8	1,6		0,8	
	2	Basalt WR 350	350	0°-90°	1	50%	0,70	1,8	1,3		0,6	
Outer Skin	3	Basalt DB 450	450	+-45°	1	50%	0,90	1,8	1,6	**5**	0,8	**3**
	4	Basalt UD 350	350	0°	1	50%	0,70	1,0	0,7		0,3	
Resin	Resin uptake						1,50	1,8	2,6	**4**	2,6	**3**
Core	Balsa	Balsa SBC 15mm					1,63	0,6	1,0			
	CAPPING	Basalt UD 350	350	0°	4	50%	0,70	2,2	1,5	**2**	1,2	**1**
	5	Basalt UD 350	350	0°	1	50%	0,70	1,0	0,7		0,3	
Inner Skin	6	Basalt DB 450	450	+-45°	1	50%	0,90	1,8	1,6	**4**	0,8	**2**
	7	Basalt WR 350	350	0°-90°	1	50%	0,70	1,8	1,3		0,6	
							total weight =		**14**		**8**	

Appendix 16. Total costs

Cost section	Cost with e-glass and PVC foam	Cost with basalt and balsa core	Cost with flax and balsa core
Hull plug cnc machined and mould	€ 50 000	€ 57 813	€ 57 813
Deck plug and mould	€ 16 500	€ 22 500	€ 22 500
Deck materials for infusion	€ 7 170	€ 8 829	€ 13 493
Hull materials for infusion	€ 9 566	€ 12 681	€ 22 121
Bulkheads and templates	€ 1 761	€ 2 129	€ 3 613
Spar	€ 40 000	€ 13 500	€ 13 500
Plywood	€ 2 165	€ 2 165	€ 2 165
Auxiliary materials	€ 9 263	€ 9 263	€ 9 263
Windows/hatches	€ 2 849	€ 2 849	€ 2 849
Electricity+ shore power+ refrigerator	€ 6 479	€ 6 479	€ 6 479
Furniture (attachments)	€ 3 136	€ 3 136	€ 3 136
Keel and keel frame	€ 18 886	€ 18 886	€ 18 886
Grommets, clamps, rods	€ 5 621	€ 5 621	€ 5 621
Tanks system (fuel, water and septictank)	€ 815	€ 815	€ 815
Kitchen systems	€ 545	€ 545	€ 545
Pumps	€ 361	€ 361	€ 361
Antifoil painting	€ 2 368	€ 2 368	€ 2 368
Pulpits and metal fittings	€ 2 384	€ 2 384	€ 2 384
Steering system and rudder	€ 16 850	€ 16 850	€ 16 850
Sanitary equipment	€ 920	€ 920	€ 920
Heating system	€ 1 367	€ 1 367	€ 1 367
Deck hardware total	€ 20 800	€ 20 800	€ 20 800
Ropes	€ 8 580	€ 8 580	€ 8 580
Total	**€ 228 382**	**€ 220 837**	**€ 236 425**