Analysis of Capital Expenditure and Time of Manufacturing of Sailing Vessels in Composite Material.

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Abstract
This work aims to provide an overview of the extensive and still unknown field of the capital expenditure to produce sailing boats in composite materials. The three basic methods for assessing the costs are presented and their theories applied to the other sectors of industry have been readapted for the sailing yachts field using the knowledge and the experience of the Trimarine shipyard. The three main methods are the analogous estimation, the parametric approach estimation and the bottom-up estimation and in this elaborate, they are applied to some real projects. In the beginning, an analogous estimating is introduced analysing a bid made on the base of a similar boat. Afterward, a cost estimation tool is presented for novel productions in composite, which is based on the parametric approach. The strength of this tool is due to regression equations gets from a database of existing vessels. The tool provides a general idea of the costs that a shipyard must deal with and in order to validate the results, the main dimensions of an existing project have been used and the final values of the tool have been compared to the value of the existing project. Following a specific request made by the shipyard's owner, implementation of their bottom-up method-based tool is developed and it basically consists on to assign a time to each layer of materials that will form the hull structure considering several factors.

1. Introduction

Although the presence of literature regarding the cost estimation for the construction of S/Y in composite materials is almost absent, literature review and data collection have been particularly important in the first research phase of this study. The purpose of this literature review is to give an insight into the main methods used in the conceptual stage of design both for construction and both for cost estimating. The first part of this chapter of the thesis, the theoretical background, wants to be useful to improve the understanding and the knowledge of the reader regarding the materials and the manufacturing processes employed for the construction of an S/Y in the composite. After that, the state of the art of the cost estimation applied to general engineering projects has been deeply studied and briefly presented in order to provide a general overview. It is recognised the difficulty to get information and data regarding the production of sailing boats, but thanks in no small amount of research on cost estimation in other fields, useful information has been obtained. This theoretical knowledge has been treated and subsequently applied to the specific sector of marine composite production. The estimation cost methods applied to the construction of boats in composite materials have the same concept of the other engineered projects but considering different concepts and variables. It is also important to note that using specific materials and/or manufacturing processes present different cost, and for this reason, several cases have been considered.

2. Definition of the problem

Engineers are conscious of the effort in terms of hours and energy that a new building project could have in order to be designed. It is certainly challenging to find univocal answers to obtain innovative and performance design solution when you are dealing with a limited budget and a restricted deadline. For that reason, the decisions made in the design phase must be accurately analysed from the economic point of view as well, and the engineers must have a business-oriented mindset. This need of versatility by the engineer figure pushed to an in-depth analysis of the economic aspects for shipbuilding and to apply this knowledge to the specific construction of sailing boats. The preponderant aspect on which this thesis is focused is the CAPEX that means capital expenditure and represents the expenses needs to develop the project from the construction and manufacturing point of view. In shipbuilding, there are different voices of cost which could be included in the calculation of the production cost, but the most significant ones for the CAPEX cost are the labour cost and the cost of materials. The most important factors that must be taken into account regarding the above-mentioned voices of cost are the labour wage rate for different country and the oscillation of the price of the construction materials over the years. The capital cost also depends on the way the ship has been financed. Cost of money refers to the average interest rate for a loan of a new building project of a sailing boat. It consists of a periodical tax that must be paid for having used the loaned money. However, in S/Y newbuilding, where not a massive amount of money is usually involved, the clients usually finance their project and maybe some of them probably appeal for lease plans or similar financial products more for tax benefits reason than for the needs of a loan. For a buyer, it is necessary to know, already in the initial stages, the price for the realisation of his project to possibly request a loan from the bank. Therefore, the shipyard must be able
to estimate as accurately as possible the cost for the production in order to provide competitive and realistic bid. Cost estimation is as challenging as a necessary phase of shipbuilding processes, which allows the shipyard to provide to the client competitive price quotes in order to have more chances to gain the contract. In the particular field of the sailing yacht, the estimation of the time and costs for the production of a high-performance vessel is entirely different from the construction of any other kind of boat because there are several processes and materials involved which can affect differently the time and the costs of a project, and for this reason, several considerations have to be made.

3. Literature review

Technological evolution is an inevitable process that aims to encourage researchers to discover "new materials" that can meet, in different fields, the needs of designers in terms of mechanical properties, durability and wide availability of use. Composite materials play a crucial role in the marine industry because due to the free competition in the market, they allow the companies to be innovative and capable of adapting to the new manufacturing processes to develop high-performance craft always lighter and more performing.

3.1 Theoretical background of composite materials

Fibre Reinforced Polymers are materials composed by reinforcement fibres and based resin matrix. The fibre-reinforcement is usually much stronger and stiffer than the matrix and gives the composite its useful properties. The matrix surrounds and holds the fibres in an orderly pattern and helps to transfer load among the reinforcements.

The corrosion resistance, the ability to mould complex-shaped structures, excellent strength to weight characteristics, low cost for series production, low maintenance and easy to repair, excellent durability and not being a magnetic material are just some of the main advantages of FRP in marine applications. The main types of fibre reinforcements used in the marine application are three:

- **The glass fibres** are widely used to produce low-cost advanced structural composite materials in the marine industry. Fibreglass presents a good tensile strength, and it is possible to find different type in the market, each one with characteristics like chemical and electrical resistance.

- **The carbon fibres** have the highest specific stiffness of any commercially available fibre, very high flexural strength in both tension and compression and high resistance to corrosion, creep and fatigue.

- **The aramid fibres** present high strength and low density giving very high specific tensile strength. Other properties are the good resistance to impact and the low modulus. The fibres are combined and assembled in order to form sheets of different warping and orientation, which provide essential properties. The main types of fabrics are:
  - **Unidirectional** are the fabrics which present the majority of the fibres oriented in one direction.
  - **Woven** fabrics are used in applications that need more than one fibre orientation. They are produced by the interlacing of warp (0°) fibres, and weft (90°) fibres in a regular pattern or weave style and their integrity is guaranteed by the mechanical weaving of the fibres.
  - **Multiaxial** fabrics consist of two or more layers of long fibres kept in position by a secondary non-structural stitching thread. The layers of fibres are arranged in 2 or more directions, and they are respectively called biaxial when are settled ± 45°, triaxial to ± 45° / 0° and quadriaxial to ± 45° / 0° / 90°.

- There is another kind of fibre called **Random**, which represents the fabrics spread uniformly but randomly.

The resins are polymers composed of long chain-like molecules, used as a matrix to create structural composite materials ensuring good mechanical, adhesive and toughness properties. They must provide excellent resistance to environmental degradation. The most typical thermosetting resins used in the marine application are:

- **The Polyester resins**, which are widely used in the marine industry thanks to their superior properties and water resistance. They are quite cheap and due to the slow natural polymerisation, requires the addition of catalyst and accelerator.

- **The Vinylester resins** are similar in their molecular structure to polyesters, but they present better resistance to water and a higher toughness compared to polyester resin.

- **The Epoxy resins** are classified as thermosetting resins and represent the highest performance resins available nowadays. They overcome any other type of resin in terms of mechanical properties and resistance to environment, in fact, they are widely used for high-performance boats for their incredible adhesive properties and the high resistance to water degradation. Epoxy resins differ from polyester resins because a hardener rather than a catalyst cure them. The hardener must take part is the chemical reaction in the correct mix ratio, otherwise, the final properties after the cure will be affected.

The cores are materials used to build hull and deck or other structural parts in a sandwich. They have the role of increasing the laminate stiffness keeping its weight low. It is known that the flexural stiffness of any panel is proportional to the cube of its thickness, therefore the core materials are generally low-
density materials used to increase the thickness and consequently the stiffness. The core plays a crucial role because ensuring to withstand taking a compressive loading without premature failure. There are several types of core materials:

- **The Polyurethane foams** are cheap, but they present inferior mechanical properties and tend to degrade over time.
- **The PVC foams** are among the most used materials in the construction of high-performance sandwich structures. They offer a well-balanced combination of static and dynamic properties.
- **SAN foams** present mechanical characteristics comparable to those of PVC foams.
- **Honeycomb** cores are extremely lightweight components made by paper or aluminium. They allow us to realise the structures with the best resistance/weight ratio.
- **Nomex honeycomb** cores material formed of paper based on Kevlar. It is becoming increasingly used in high-performance components due to its high mechanical properties, low density, and good long-term stability.
- **Wood** cores like balsa or cedar can be defined as a natural “honeycomb”, because its structure, on a microscopic scale, recalls the hexagonal cell of the artificial ones. Balsa presents high compressive properties and excellent thermal insulation but has a high minimum density.

### 3.2 The manufacturing processes

Manufacturing processes are a preponderant factor that influences the properties of the final products. The most used manufacturing processes from the shipyard are:

- **Hand lay-up** is one of the most common and inexpensive methods used in the marine industry. Resins are impregnated by hand usually by rollers or brushes, and the laminate is left to cure under standard atmospheric conditions.
- **The Vacuum Bagging** can be considered as a direct extension of hand lay-up, and it consists in creating the vacuum of the laminate during the cure to allow reaching a product of better quality by eliminating the presence of bubbles in the resin and improve the consolidation.
- **Pre-preg low temp** use fabrics that are impregnated by machine by the manufacturer using a resin system that polymerises only when it is subjected to a specific temperature. For that reason, the materials are stored frozen to prolong storage life. The cure is achieved at temperatures from 60-100°C due to the chemical composition of the resin.
- **Pre-preg Moulding** consists of the pre-impregnated fabrics which are laid up by hand into a mould surface; they are vacuum-bagged and then heated between 120-180°C to allow the reflow and the cure of the resin.

- **The infusion** process is one of the most developed and applied methods for the production of high-performance craft. In infusion, the fabrics are laid up as a dry stack of materials into the mould and covered with peel ply and other non-structural resin distribution fabrics like the bleeder, the release and the breather. Subsequently, the resin starts to flow into vacuum bagging using the suction of a pump.

### 3.3 State of the art of cost estimation methods

Cost estimation is an engineering art which, applying scientific techniques, allows to predict the quantity, cost and price of the resources required by the scope of a project. Detailed work planning and careful assessment of manufacturing costs and times will bring benefits for the whole duration of the project as well as to define its success or failure. Significant economic accomplishments are obtained only if the shipyard adopts an accurate cost assessment process. (Bertram *et al.*, 2005; Caprace, 2010; Caprace and Rigo, 2012).

Predict the costs already at an early project phase with enough accuracy provides enormously benefit, and it is well known that cost assessment is crucial during the early stages of project development because it influences future decisions of choice.

<table>
<thead>
<tr>
<th>Building stage</th>
<th>Cost of the stage</th>
<th>Impact on total building costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preliminary design</td>
<td>3%</td>
<td>50%</td>
</tr>
<tr>
<td>Other design stages</td>
<td>7%</td>
<td>25%</td>
</tr>
<tr>
<td>Ship production</td>
<td>90%</td>
<td>15%</td>
</tr>
</tbody>
</table>

Table 1 shows the enormous impact on the total cost of the preliminary design stages; in fact, the influence of the initial decisions is around 80% of the whole project.

Although one can be careful regarding the use of the best method of estimation and the goodness of the input data, in the estimation of a project, there will always be a certain degree of uncertainty in the estimation, mostly in the design phase. This degree of uncertainty will reduce along with the project development because the data and the information that was previously unknown become clearer. The variables that affect the accuracy of estimation are several and depends on the economic-industrial organisation of each shipyard.(European Commission, 1998; Shetelig, 2013)

The cost estimation methods that can be employed in a project are various and different. The three methods considered in this elaborate are

- **Analogous Cost Estimation** is a top-down method, it is easily understandable and developable considering existing projects, that are similar to the one in a development phase. Taking as reference the
data available for those projects is possible to make an analogy of the costs and time of the new project. It consists basically of finding and comparing the similarities between the projects already completed and the project under analysis. (NASA Executive Cost Analysis Steering Group, 2015)

- **Parametric estimation** uses historical data and statistical techniques to predict future costs. This technique expresses the cost through analytical functions coming from a set of variables. The analytical functions are defined as CERs and represent the relationship between the cost drivers parameters and the cost. The linear regression is the most considered function for parametric estimation, and it presents this shape

\[ y = \alpha + \beta x + \epsilon \]

The more the database is rich and detailed, more the equations will provide realistic and precise values.

- **The bottom-up estimation method** is considered the most specific method engineering projects because it provides a meticulous cataloguing of the costs, of the progress and time tracking. It is based on the work breakdown structure (WBS), and it is quite easy to understand. The Bottom-up approach requires that the project is analysed in detail to identify all the components at the lower level of the WBS. Every single component is estimated separately from the others, and the result of the estimates is finally aggregated to obtain the total project estimate.

This technique is useful only if there is very detailed information on the project or if something identical was already built. In the absence of detailed information, it is necessary to proceed with assumptions which must be well justified and documented.

4. Study cases

The methods above mentioned will be applied to the construction of the sailing boats, showing the different stage of use and the specific features for each project. Using the provided materials and information will be initially presented a bid for an IRC class of 44 feet using the analogous estimation, on the base of a similar ship of the same class but smaller than the one that must be evaluated. Subsequently, thanks to the help, the materials and the information provided by Trimarine, the parametric estimation, created using Excel, will be presented and explained in detail. To conclude, a bottom-up estimation will be analysed to improve and implement their model of the spreadsheet, joining the scantling process to the time for laying up and laminate each layer.

4.1 Estimation by analogy

The first study case presented is the application of the analogous estimation method in a real case. This method was used by Trimarine shipyard in 2017 to provide a bid for a potential client which asked for the construction of an IRC class of 44 feet. In the past, Trimarine performed two boats of the same class and similar dimensions. The first project is an IRC42’ Class built-in carbon pre-preg with honeycomb Nomex core and foam core cell, while the second is an IRC 39’ built-in Sprint E-glass with foam core. For the realisation of the offer, a spreadsheet was created which present the following parts:
Initially, the calculation of the areas and the perimeters were obtained on the base of the 3D drawing of the IRC 42’ and imposing some assumption; they were increased and readapted for the new boat. In the second spreadsheet called “Hours Estimation”, the hours needed for the construction of the structure using the infusion process are estimated using several parameters that express the hours per square meter of surface or the hours for a linear meter in case of bonding or joining. Presenting this part of the estimation method, an overview of the procedures and the steps of the construction applying the infusion process is given and using the WBS of the previous projects is possible to estimate in detail each step and component. In fact, from the bottom-up final balance of IRC42’, a WBS table with high-level of details of each element was taken to have a clear insight about the process developed in the previous project and to increase the level of accuracy of the estimation. The main groups, and some example of their sublevels in parentheses, for the WBS of the construction process, are:

- The tooling (Plugs and moulds);
- The construction (hull, deck, internal structures etc.);
- Joining on Hull (Internal structures, internal furniture etc.);
- Hull & Deck joint assembly;
- Painting & Finishing (Interior, exterior, hull, deck etc.);
- Systems Supply & Installation (Deck hardware, mast & rigging, electric & electronic, steering & propulsion etc.);

The shipyard, in order to contain their cost and the price for the customer, suppose to construct the IRC44 using the same mould, so the same shape of IRC42. For that reason, the hours for tooling are considered just for the alteration of the existing moulds.

The estimators of Trimarine are used to use a parameter of 14 h/m² based on the experience and considering the skills of their workers for the infusion technique. Using this parameter, the hours for the construction of the hull and of the deck were calculated, and the value obtained includes the hours required to lay up the materials and to perform the infusion process. Nevertheless, an important consideration must be made about the employ of different manufacturing process: in fact, considering the hours of existing project, it was estimated the fabrication of the hull, the deck, and the other structures using the infusion of fibreglass that is so much faster compared to the carbon pre-preg construction which requires a vacuum bagging every two layers to compact them. This justifies the values of higher hours for the IRC42’. For the other internal structures like the bulkheads, the longitudinals, etc., a parameter of 12 h/m² has been considered while the parameter used for the calculation of the hours to produce the interior furniture has been 15 h/m².

For the bonding and the joining on the hull of the internal structure and the interior furniture, a parameter of 3 h/ml has been considered. For the joining of the deck and the hull among them and the bonding of the transom, the hours were estimated using respectively 3 h/ml and 4 h/ml.

For the painting & finishing, a parameter of 12 h/m² was considered for the exterior surface of the hull, and a parameter of 6 h/m² was used for the exterior surface of the deck. For the interior finish, fairing and painting, a parameter of 3 h/m² were considered both for the hull both for the deck. For the system supply and installation has been estimated the same hours of the previous project on the base of the installation made for the IRC42’.

Since the hours of labour represent the most significant voice for the cost of construction, multiplying the hours for the labour wage, the labour cost is easily obtained. Using the sheet which takes the name of “scantling” it was possible to estimate the cost of the materials needed for the construction. In the “scantling” are described in detail all the materials used to make up the boat. Each element and part of the ship is divided into the layers in which it is composed and in this sheet are listed for each layer the fibre fraction in percentage, the fibre weight, the thickness of each ply, the cured ply weight, the area, and the quantity of resin needed.

Once the scantling is completed, it is possible to calculate the cost of the material through the sheet “BOM”, which means the bill of materials. From scantling, the area of each material is known, and once the number of the sheets or the rolls of each material is calculated, it is possible to obtain the cost of each material multiplying its unit price for the quantity needed.

Once the most relevant parts of the cost of construction have been estimated, a long list of equipment and devices still misses in order to complete the bid. In fact, for the deck hardware, the electric and electronic systems, the onboard systems and interiors fit-out, and in particular, the mast, the keel, the propulsion and the steering system were taken into account and add to the total cost. Since to
have an exact estimate of these last cost items, it would take weeks if not even months of time, as it would be necessary to request a quotation of the price of each element from the suppliers or search in the catalogues, they have been estimated and added considering the cost of the equipment and their quotation from the previous project of IRC42. Once all the costs are estimated, they were gathered in the summary sheet to show the provenience of each voice of cost. To conclude the bid and provide a price to the client, a mark-up margin express in percentage is added to the total cost to guarantee a profit for the shipyard.

Particular attention was paid regarding the difference between the manufacturing process applied for the IRC42’ and the technique considered for the future construction of the IRC44’, and the experience of the shipyard’s project manager has been crucial to estimate the hours. The carbon pre-preg process, used for the previous project, expects different labour hours for its development compared to the hours to realising the infusion technique for the construction of IRC 42’. The pre-preg process used for the IRC42 allows to obtain manufacture very lightweight, but it requires higher labour hours to perform because it needs vacuum bag every two/three layers to compact them.

4.2 Parametric estimation

The tool created by Excel allows the shipyard to get a rough estimation of the costs of a new building project just using the basic dimension of the ship as initial data. It is important to say that due to the confidentiality of this cooperation with Trimarine, all the values inside the databases created in the estimation tool have been hidden. Input&Surface is the first sheet that must be used. It allows inserting the main dimensions of the boat. Using some basilar formulas, which require just the application of the boat geometries, the surface areas of the hull and the deck can be estimated. As mentioned, these areas and the length of the boat are used as independent variables for the regression analysis in the next calculations.

In this first sheet, in addition to the primary dimension and the calculation of the surface areas is possible to set the wage salary, which in this case has been chosen as the average value of salary in Portugal for this kind of worker, and trough two drop-down list cells is possible to choose the type of mould and the combination among the material and the manufacturing process. Both are going to influence the following calculations. Another table is the actualisation of the materials’ cost over the years which, with a simple formula, allows for correcting the value of the cost of the materials for the boats built many years ago.

The second sheet is called Group I - Tooling construction and represent the set of tasks for the construction of the plugs and the moulds. This phase is such an essential and complex part of the process that it would deserve a separate discussion, as they can be built in several ways and with different materials and for this reason, some considerations must be made. For example, a sophisticated plug made by CNC and a female mould in composite, due to its high cost, is justified from many units produced in series or for high-performance racing boats. A database of already made projects has been created in this first group to be able to perform the regression analysis. The dependent variables (hours/cost) and the independent variables (length/area) of each project are selected and, by using scatter plots, a cloud of points appears. The best fit lines are added, and thanks to its equations, it is possible to know how the hours or the cost varies if the length or the area change.

![Figure 4 - Best fit lines and regression equations for mould hours of labour](image)

In the Group II - Structures construction, as made for the previous group, a database has been created with the information of existing projects reporting the hours of labour and the cost of the materials for the construction of the structures. As will be shown later, this group represents the most consistent part of costs in terms of hours and materials for a project. In the following Table 2 is shown the structure of the database.

<table>
<thead>
<tr>
<th>Material</th>
<th>Length [m]</th>
<th>Surface [m²]</th>
<th>Hull [Cost]</th>
<th>Deck [Cost]</th>
<th>Number of moulds</th>
<th>Hours (per m²)</th>
<th>Total [Cost]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>5</td>
<td>10</td>
<td>100</td>
<td>50</td>
<td>2</td>
<td>10</td>
<td>500</td>
</tr>
<tr>
<td>Carbon</td>
<td>5</td>
<td>15</td>
<td>200</td>
<td>70</td>
<td>3</td>
<td>15</td>
<td>750</td>
</tr>
</tbody>
</table>

![Table 2 - Structures construction database](image)

In the same way, already explained for the Group I, the scatter plots have been created by using the variables in the database shown in Table 2, and the regression equations have been obtained. The equations allow estimating the values of the hours of labour for the construction of the structures when the length and the surfaces area vary.

![Figure 5 - Best fit lines and regression equation for the cost of materials of the construction of the structures](image)
As reported in Figure 5, have also been created the plots considering the two main different combinations of materials/manufacturing process present in the database in order to justify the comparison of the data. Moreover, in the second group have also been created a depth analysis of construction hours using the complete and detailed information of three existing projects. The structures construction process has been broken-down and to each task has been assigned the correspondent hours of work in order to obtain a regression equation which defines each task of the construction process. The same has been made for the previous Group I.

In addition to that, also for the estimation of the cost of the materials, a depth analysis has been performed. Through three specific projects, a table with specific information regarding the lamination of the hull and the deck has been created, and it was possible to get the square meter of fibres used in the construction. Thanks to this information, a correlation between the surface area of the hull plus the deck and the area of materials needed have been created. Subsequently, imposing a ratio between core and the fibres and knowing the fibre weight fraction between fibres and resins, the cost of each material has been estimated simply multiplying its area for the price per square meter.

Comparing these values to the ones obtained before in the general calculation of the materials’ cost for Group II, it is possible to see that the estimation made for the combinations of materials and processes carbon pre-preg and E-glass infusion present similar results if it does not consider the cost of the consumable. So, it proves that the estimations are reliable.

In Group III – Fairing and painting, the hours of labour and the cost of materials for all the phases of the painting cycle have been estimated using the scatter diagrams and subsequently, the regression equations. It is important to note that the moulds types have to be considered because the use of female or male mould will affect the hours of labour for this group.

In Group IV - Supply system & Installation and Group V - Propulsion & Steering System represent the last two parts of the tool which contains some subgroups: Deck hardware, Rigging & Running, Electric & Electronic, On-board system Engine&Propeller, Steering System and Keel. Due to the lack of information regarding the hours of work needed to the installation and due to the enormous variety and quality of components on the market, proportional parameters and some corrective factors settled with the experience of Trimarine were imposed to estimate the hours of labour and the costs of materials for this group.

### 4.1 Deck hardware

<table>
<thead>
<tr>
<th>HOURS</th>
<th>Proportional parameter</th>
<th>Proportional parameter for Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>$51.90$</td>
<td>$0.7$</td>
<td>$17.46$</td>
</tr>
</tbody>
</table>

### 4.2 Rigging & Running

<table>
<thead>
<tr>
<th>HOURS</th>
<th>Proportional parameter</th>
<th>Proportional parameter for Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>$22.99$</td>
<td>$0.7$</td>
<td>$0.7$</td>
</tr>
</tbody>
</table>

To conclude the parametric estimation tool, the resume sheet has been created to summarise all the voices of cost and provide the total estimation of hours of labour and cost of materials as well as the total cost of the project. In the following pie charts are shown the influence of the labour cost and materials cost and the influence of each group on the total cost in percentage.

**Figure 6 - Estimation of the onboard system with proportional parameter**

**Figure 7 - Influence of each Group for labour, materials cost and total cost**

In this conclusive part of the project is also reported the tendency of the learning curve, which is a graphical representation of how increasing the skills in repetitive work leads to a reduction of the hours of work.

**Figure 8 - Learning curve of the hours of labour**

The learning curve is also considered for the cost of the materials because it is evident that for a big order of materials is possible to get a discount from the supplier.

### 4.3 Implementation of scantling for bottom-up estimation
Trimarine requested to implement their spreadsheet for bottom-up cost estimation by adding to the scantling process the estimation of the labour time for each layer. The sheet “Scantling” represents an important part of their estimation process because it goes in-depth to the construction process of the structures and for each structural part shows the type, the features and the number of materials in terms of area and weight.

### Table 3 - Scantling of the hull

<table>
<thead>
<tr>
<th>Material</th>
<th>Width</th>
<th>Length</th>
<th>Area (m²)</th>
<th>Length (m)</th>
<th>Width (m)</th>
<th>Cross-section (cm²)</th>
<th>Deadweight (ton)</th>
<th>Hull Thickness (mm)</th>
<th>Weight (ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Hull</td>
<td>34%</td>
<td>80%</td>
<td>397.7</td>
<td>1</td>
<td>79.3</td>
<td>31.95</td>
<td>11.587</td>
<td>0.8</td>
<td>2.9</td>
</tr>
<tr>
<td>A. Hull</td>
<td>54%</td>
<td>80%</td>
<td>543.7</td>
<td>1</td>
<td>72.3</td>
<td>32.01</td>
<td>12.823</td>
<td>0.8</td>
<td>2.9</td>
</tr>
<tr>
<td>A. Hull</td>
<td>54%</td>
<td>80%</td>
<td>543.7</td>
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</tbody>
</table>

A table with correction coefficients has been created considering, for example, that prepreg fabrication process requires more time if compared to the infusion or unidirectional fibres need more time respect to multiaxial or woven fabrics. Even the skills of the worker are an essential factor to consider.

### Table 4 - Correction coefficients for the scantling implementation

<table>
<thead>
<tr>
<th>Method</th>
<th>Water up</th>
<th>Infusion</th>
<th>Pre-preg</th>
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</thead>
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<td>1.3</td>
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<td>1.2</td>
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</tbody>
</table>

Thanks to the expert judgment of Sebastiano, the days needed to lay up the different parts of the hull have been assumed. For example, to lay up the outer skin have been assumed three days, the same for a layup the inner skin while for the core, seven days have been considered. Multiplying them to the number of working hours per day, that in this case have been assumed in a compressed way as 10 hours per day, the number of hours for each layer that compose the construction of the hull has been obtained.

### Table 5 - Implementation of hours estimation for scantling

<table>
<thead>
<tr>
<th>Hull</th>
<th>Deck</th>
<th>Ballast</th>
<th>Longitudinal</th>
<th>Transverse</th>
<th>Engine Room</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coeff.</td>
<td>1.2</td>
<td>1.1</td>
<td>1.2</td>
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</table>

Considering that the hours for the construction of the hull of the boat analysed with the analogous method is 978 hours using a parameter of 14 h/m² for a surface of 70, and the value obtained by the implementation of the spreadsheet for the bottom-up method is of 982 hours, it is possible to state that the implementation for the scantling sheet provides a good estimation of the hours for laying up every single layer.

### 5. Overheads

In addition to the direct costs of a project that have been already presented during the application of the estimation methods, which are identified as labour costs and costs of the materials involved in a specific project, there are several indirect costs that the shipyard must face. These costs, as it can be easily guessed, are those productive factors that are used simultaneously for several projects and that do not have a direct link with the production. Anyway, indirect costs can be summarised as follows:

- The cost of personnel supervising projects (for instance, the project manager);
- Rents of the offices in which the company operates;
- Costs of utilities (electricity, water, telephone, internet, heating);
- Administrative costs;
- The costs of equipment shared by multiple projects.
6. Discussion of the results

The applications of the three methods provide some interesting results. Regarding the presentation of the method by analogy, it is interesting to note that the estimation of the time of construction is made just applying some parameters of h/m² for the lamination and h/m in case of bonding and it might seem something completely unrelated to the method of estimation by analogy. These parameters have been used for the difference between the processes considered. It is important to highlight that the prepreg process requires almost the double of the time comparing to the infusion process because of the necessity to apply vacuum bag to the prepreg sheets every two layers in order to obtain a compacted product. Anyway, the analogy method is used and enter into the calculations thanks to many other aspects like the similarity of the shapes and dimensions of the surface area among the hulls, the use of the same mould, the same arrangement of the internal structures and it encounter its maximum benefits for the application on the systems and devices installed on-board which represents a consistent part of the cost for the realization of a project.

For the development of the parametric estimation tool, the surface area estimated has been compared with the ones of the existing project obtaining values similar, with a range of accuracy is between the 3% and the 5%. The hours of labour for the construction of the structures represent the most significant part of an S/Y building project with 48% of the influence. For what concern the cost of the materials, the systems and the devices installed on-board represent most consistent part with the 41% of the total cost of materials compared to the 24% of the materials for the construction of the structures.

It is really interesting the comparison between the estimation by analogy and the parametric estimation. It is noteworthy that, the difference in the total cost is quite different between the two methods, in fact, the estimation by analogy presents a total cost of approx. 530.000 € while the parametric estimation present 609.000 € and they present an error of 13%. This gap can be justified probably to the different values of cost of the devices, equipment, systems and installation. In fact, for the estimation by analogy the costs and the hours of labor for these groups of the project have been considered the same of the existing IRC42 project, while in the parametric estimation they have been estimated using the proportional parameters, that provide different values.

This seems the most plausible hypothesis of the difference of the total because the hours and the cost of the materials for the construction of the structures present results quite similar, although they have been estimated differently, with other assumption and criteria. Considering the sum of the total hours of labor in the estimation by analogy, a value of 7165 hours has been obtained, that is similar to 6881 hours obtained considering the length of the vessel in the parametric estimation. Moreover, as already said, the value of hours for the construction of the hull is close considering the estimation by analogy (978 h), the implementation of the scantling (982 h) and are just a little bit different respect the parametric estimation (1561 h).

Similar values have been obtained in the two estimation methods also for the materials’ cost. Considering the same E-glass fibre materials and the same infusion technique, the estimation by analogy give a value 52.700 € of materials’ cost while the parametric estimation provides a 57.000 €.

Conclusions

In the development of this work, the most important aspects for the estimation of the costs of a high-performance S/Y project in composite materials were highlighted, and three different methods of estimation of the costs applied to real cases have been created, and a basic tool for the parametric estimation has been realised.

In the end, it is possible to state that two estimation scenarios are, in general, identified as the most common. The estimation by analogy or a parametric estimation when historical data are available, and the bottom-up estimation ever times the work state of the design is enough developed with the large availability of information.

The estimation of the time for a construction project represents the most complicated part of the process of the estimation itself. It must always be kept in mind that for each project, different obstacles will be encountered that will slow down the work and increase the labour hours for their resolution. It is essential to rely on the experience in order to expect the criticalities of each project, which must be identified and taken into consideration for the estimation.

In the realisation of a high-performance S/Y, the most preponderant part of the cost of the materials is related to the systems and onboard equipment and devices. The estimation of these items is still a difficult task for shipyard personnel because there is an enormous amount of types and brands in the market and their installation depends a lot on the characteristics of the boat, the budget and the needs of the owner.

Parametric estimation represents the simplest and fastest way to estimate the costs for the realisation of a project when there is a rich database of existing projects. Is possible to develop and use, through the parametric estimation, cost estimating relationships to evaluate and express the relative consequences changes of high-level performance requirements have on the total shipbuilding cost.
In addition to this conclusion, it is essential to state that, due to the not florid availability of data, in this elaborate was not possible to perform an accurate “what if” analysis considering different manufacturing processes and materials used. It is also essential to know that some improvements must be performed in the implementation of the bottom-up estimation regarding the parameters and the correction factors used. A factor of inefficiency between a half-hour and one hour must be considered for the breaks that the workers usually have during the day for coffee, toilet, smoking, etc.

Acknowledgement

This work has been performed in close collaboration with the Trimarine shipyard, which has been highly appreciated.

References

Germanischer Lloyd (2003). ‘Rules for classifications and construction of Ships, Part 3, Section 1 & 2. Hull structures and Mast and Rig.