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HULL'S MANUFACTURING COST STRUCTURE

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Summary

This study analyses the structure of costs of several processes associated with the shipbuilding industry. The analysed productive processes are: cutting preparation, steel plate cutting, hull plates and stiffeners forming, associated transportation and assembling of plates and profiles, and finally the welding.

The methodology allows a shipyard to identify the main costs related to the manufacturing of the hull and the aspects that should be improved to increase productivity.

The methodology adopted may easily be adjust by each shipyard creating a work database in order to improve and update these formulas by adding new corrective coefficients based on the type of the built ship or construction complexity of certain ship blocks.

Two independent case studies that took place at different Portuguese shipyards and covering different aspects of the steel hull shipbuilding processes are presented.

The first case study considers time and cost analysis of the processes associated with cutting preparation made by the design office, cutting/marking of steel plates and forming processes of stiffeners and hull plates, required for the construction of an 83m Hopper Barge.

The second case considers the time and cost analysis of stiffeners cutting, steel plates and stiffeners assembly and welding, associated with the building of several blocks of an 80m fisheries supporting vessel.

Key words: *Ship Construction; Budget breakdown; Cutting; Welding; Transport; Bending; Forming; Preparation; Time and Cost Analysis;*

1. Introduction

The full knowledge and understanding of the cost structure of a given production process is always of high importance for the budgeting of a given work order. Only then it is possible to make the best budget approach so that a shipyard can be competitive in the middle of many others in the shipbuilding market [1].

It is intended to make a budget breakdown, i.e. the decomposition of the total cost of the ship's hull construction in several smaller parts each one associated to a given cost center, to evaluate the percentage of each of the cost centers that make up the final cost. Note that when talking about the ship's hull in this study, it implies the inclusion of its superstructure, but always excluding any appendices and outfitting.

It is proposed to find tools that allow to make simple estimates, quick and realistic budgeting for a given ship work. These estimates are to be found by means of statistical analysis of shipbuilding processes times and costs of several blocks of a ship.

These estimates can then vary for different types of blocks by an adjustment coefficient associated with block construction difficulty degree, i.e. having two blocks with similar weight they have different cost estimates according to the complexity of their construction.

2. Analyzed Productive Processes

This study analyses the following productive processes of steel hull manufacture: work preparation, cutting, forming, assembly, welding and transportation.

2.1 Work Preparation

The processes related to the detail engineering, made either by engineers or by designers, involving the generation of all parts in appropriate software. These parts are based on the construction plans of the ship (block division, transversal sections, floor plans, longitudinal section, shell expansion, etc.). They create a database of all the hull steel parts that will be exported to the programs that perform the necessary coding of the several parts nesting for the automatic cutting machine. In parallel, 3D models are generated which include all the parts in their final positions of assembly, in order to make a dimensional control and validation of the cut and also to generate the auxiliary drawing assembly of the various panels, sub-blocks, profile cutting and forming.

2.2 Cutting

The processes taken into account in this study were the plasma cutting, oxy gas cutting and mechanical cut.

The plasma cutting is mostly used for the steel plate parts cutting, the oxy gas cut is used for cutting high thickness steel plates and finally the mechanical cut is the primary process for cutting reinforcement profiles.

2.3 Forming

The mechanical forming is a set of processes used to transform a flat surface in a desired curved surface by plastic deformation [2]. This study analyses shell plates forming process and reinforcement profiles bending, which include press rollers, flame heating torches, portal presses and stiffeners benders.

2.4 Assembly

The processes analyzed during this study for the assembly include only the SMAW welding type used for stiffeners, frames and bulkheads pre-assembly and indirectly the necessary means of transport for moving frame parts, stiffeners, panels or subassemblies.

2.5 Welding

The welding processes taken into account in this study were the Submerged Arc Welding (SAW), the Shield Metal Arc Welding with coated electrodes (SMAW) and Flux Cored Arc Welding with gas protection (FCAW variant of MIG) [3].

In addition to the welding technologies listed previously there are also available, alternative technologies for cutting and welding [4], but still with a very limited implementation by the small shipyards. There are several studies of new welding processes application [5], new types of welding and hybrid laser technologies that reduce thermal distortion of panels, reducing costs rework [6, 7] and also the use of new production methods in order to increase productivity in welding [8].

2.6 Transportation

Although this is not a productive process it is usually involved with the other 5 processes mentioned before and it takes some share on the final costs structure of the steel hull construction.

On this study it was observed the use of magnetic gantry cranes for steel plates transportation, overhead gantry cranes used to move assembled subsets and blocks, roller transporters and semi-trucks to carry the sub-assemblies and ship blocks, mobile cranes and cargo cranes used for panels and sub-assemblies turning over and also for short blocks local shifting, forklifts used to carry equipment, supplies, stiffeners, small steel ship parts and also used in the transport of small ship subsets and panels turning over and finally heavy lift floating crane used to load ship blocks into cargo barges in case they need transportation by river or sea to their final assembly shipyard.

2.7 Main Costs Involved

The main costs involved on the above activities and considered in this study, are manpower, energy and consumables.

The manpower to be taken in account on the involved shipbuilding processes are the following: work preparers, cutting machine operators, crane operators, steelworkers, work supervisors, marine engineers, cutting/griddling workers, transport handling personal, assembly workers, welders and work apprentices. The relevance of the type of manpower in terms of the shipbuilding cost structure is the labor cost values and the productivity of each worker, which is obviously associated with the equipment that each one uses.

The main source of energy of a naval shipyard is electricity, mainly three-phase current that is used to power large electric motors and other heavy load machinery. The secondary source might be the use of fossil combustibles, such as fuel and diesel to power engines.

The consumables materials of a shipyard are primarily associated with the cutting and welding processes.

Secondary processes that might require supply materials are the edge, surface and weld fillets grinding. This requires constant supply of cutting and abrasive discs to be used in portable grinding machines.

3. Structure of production costs

Any shipbuilding will always pass through the following phases [9, 10], with their respective associated costs:

- Contract signing
- Basic project
- Detail production project
- Ship hull construction
- Outfitting (piping, electricity, machinery and systems)
- Sea trials and certification
- Ship owner delivery

In between the above mentioned phases there will also exist stages of quality control, transportation, supervision and also plan approval from shipyard, marine design office, ship owner, classification societies and maritime flag authorities.

This study is solely focus on production phases (detailed engineering for production) and the phase of hull construction, except the union of blocks.

Within the construction phase of the hull, which is the main purpose of this study, we have the following steps:

- Parts, plates and stiffeners cut
- Plate union (bulkheads, floors and shell)
- Assembly and welding of frames and stiffeners to form panels and subsets
- Union of subsets to form ship blocks
- Union of blocks to form the whole ship

On the economic side of each one of these phases, it can be said that the costs are monetary measures of financial efforts with which an individual or organization must handle in order to achieve its objectives. These objectives imply the use of services or goods that enable the creation of new products or services [11].

A cost structure can be considered as the set of expenses that a given company has to take into account in the manufacture of a product or in providing services. Each expense is associated with a cost center that in turn is associated with a type of activity.

It is generally accepted that the cost of manpower reaches half the construction cost of the vessel's hull [12]. However, it is certain that largely depends on the complexity of the equipment and type of vessel, as in the case of a war vessel [13, 14], or a cruise ship, the latter reaching 60% [15]. On the other hand the proportion of the construction costs of a steel hull is divided into ¼ for the material (steel) purchase and ¾ in labor [16].

There are already several computer programs available on the market that address effectively the budgeting of shipbuilding, taking advantage of large shipyards production databases, combined with analytical cost models and dividing the hull construction into several cost parcels. There is for instance the SPAR ESTIMATE that uses the PODAC model [17, 18]. On the other hand, it starts to be usual the development of own software tools at each shipyard that solve and analyze shipbuilding production costs [19].

Costs can usually be indexed to weight (€/t), to distances (€/m), time (€/h) and required man-hours (Mh).

These relationships between variables of time, weight, distance, money, among others, are generally called CER (Cost Estimation Relationship) [1]. The CER is developed directly from measurements on a single physical attribute of a given activity and it is a quantity or measuring unit of the cost in man-hours necessary to perform the activity.

Table 1 presents some of the most common relationships.

Table 1. Typical cost estimate relationship units

Process	CER	Process	CER
Steel preparation	Mh/t	Pipe outfitting	Mh/m
Steel fabrication	Mh/t	Outfit fittings	Mh/EA
Block assembly	$Mh/m_{welding}$	Block erection	Mh/t
Block painting	Mh/m^2	Cargo hold	Mh/m^2

This study intended to divide and analyze six cost centers directly connected with the construction of a ship's steel hull (excluding the purchase of steel). Thus it can be said that the structure of costs in construction of a steel hull can be separated in a simple way in the following cost centers each one associated with a production process:

- Work preparation costs;

- Cutting costs;
- Transportation costs;
- Forming costs;
- Assembly costs;
- Welding costs.

For each one of these costs centers the idea is to apply a generic formula of the following type:

$$C_{\text{Process}} = \begin{bmatrix} \text{Labour cost} + \text{Energetic cost} + \\ + \text{Consumable materials cost} + \\ + \text{Equipment depreciation cost} \end{bmatrix} \text{ [€]} \quad (1)$$

The energy cost represents the electricity spent with operation of equipment, materials costs are related to expenditures with supplies and materials used by the process and finally the depreciation costs that include used equipment amortization, maintenance and devaluation. These 3 referred costs tend to be lower than the labour costs.

3.1 Work Preparation Costs

The following costs are considered for the work preparation: cost of PC's (depreciation cost), energy cost, cost of software license (to be incorporated in the cost of equipment depreciation), labor costs of work preparers, training costs (included in cost of labor), culminating in a cost equation similar to the presented:

$$C_{PRE} = \left[\underbrace{\left(n_p \times S_p \times h_p\right)}_{Labour} + \underbrace{\left(K_e \times P_e \times h_p\right)}_{Electricity} + \underbrace{\left(C_d \times h_p\right)}_{Depreciation} \right] \text{ [€]} \quad (2)$$

n_p – Number of Work preparers [M]

S_p – Work preparer wage [€/Mh]

h_p – Work preparation time [h]

K_e – Electricity consumption [kW/h]

P_e – Electricity price [€/kW]

C_d – Depreciation cost [€/h]

In order to simplify and correlate these costs with the built block weight the equation is rewritten as following:

$$C_p = P_b \cdot \left(\gamma_b \cdot CER_p \cdot MDO_p + CEQ_p\right) \text{ [€]} \quad (3)$$

P_b – Block weight [t]

γ_b – Block complexity coefficient

CER_p – Work preparation cost estimate relationship [Mh/t]

MDO_p – Work preparation labour cost [€/Mh]

CEQ_p – Work preparation equipment costs [€/t]

3.2 Cutting Costs

Regarding the cutting costs, one can take into account the following itens: cutting equipment (purchase / rental, amortization, leasing, devaluation, maintenance), energy, cutting gases, cutting operators, training, resulting again in a series of equations costs similar to those given below.

For the case of plasma cutting:

$$C_{PLA} = \left[\begin{array}{c} \underbrace{(n_{tc} \times S_{tc} \times h_c)}_{Labour} + \underbrace{(K_e \times P_e \times h_c)}_{Electricity} + \\ + \underbrace{(K_{Ar} \times P_{Ar} \times h_c)}_{Plasma\ Gas} + \underbrace{(C_d \times h_c)}_{Depreciation} \end{array} \right] [€] \quad (4)$$

n_{tc} – Number of Cutting technicians [M]

S_{tc} – Cutting technicians wage [€/Mh]

h_c – Cutting time [h] ($h_c = \frac{d_c}{v_c}$)

v_c – Cutting speed [m/h]

d_c – Cutting length [m]

K_{Ar} – Plasma gas consumption [kg or m^3/h]

P_{Ar} – Plasma gas price [€/kg or m^3]

For the case of automatic oxy-gas cut one can have the following costs formula:

$$C_{OXI} = \left[\begin{array}{c} \underbrace{(n_{tc} \times S_{tc} \times h_c)}_{Labour} + \underbrace{(K_e \times P_e \times h_c)}_{Electricity} + \\ + \underbrace{(K_O \times P_O \times h_c)}_{Oxygen} + \underbrace{(K_A \times P_A \times h_c)}_{Acetylene} + \underbrace{(C_d \times h_c)}_{Depreciation} \end{array} \right] [€] \quad (5)$$

K_o – Oxygen consumption [kg or m^3/h]

P_o – Oxygen price [€/kg or m^3]

K_A – Acetylene consumption [kg or m^3/h]

P_A – Acetylene price [€/kg or m^3]

For manual oxy-gas cut one has the following costs equation:

$$C_{MOXI} = \left[\begin{array}{c} \underbrace{(n_{tc} \times S_{tc} \times h_c)}_{Labour} + \underbrace{(K_O \times P_O \times h_c)}_{Oxygen} + \\ + \underbrace{(K_A \times P_A \times h_c)}_{Acetylene} + \underbrace{(C_d \times h_c)}_{Depreciation} \end{array} \right] [€] \quad (6)$$

And finally, in the case of mechanical friction cutting:

$$C_{MEC} = \left[\underbrace{(n_{tc} \times S_{tc} \times h_c)}_{Labour} + \underbrace{(K_e \times P_e \times h_c)}_{Electricity} + \underbrace{(C_d \times h_c)}_{Depreciation} \right] [€] \quad (7)$$

The largest share of the previous cutting costs is always related to labor. So one should separate the costs of labor and join all the other in a single parcel, such as acquisition costs, maintenance, depreciation of equipment and electricity/gases cutting costs.

These costs will be estimated in direct relation with the produced weight of steel variable according to the following simplified equation:

$$C_c = P_b \cdot (\gamma_b \cdot CER_c \cdot MDO_c + CC_c + CEQ_c) \; [€] \quad (8)$$

CER_c – Cutting cost estimate relationship [Mh/t]

MDO_c – Cutting labor cost [€/Mh]

CC_c – Cutting consumables cost [€/t]

CEQ_c – Cutting equipment costs [€/t]

3.3 Transport Costs

The costs for the transportation equipment are not easily quantifiable. But it can be said that they are related to the cost of the equipment itself (purchase/rental, leasing, depreciation, maintenance, etc.), operators labor costs and energy costs (electric or fuel). Note that some of these costs may already be included in a rental final price.

In the case of electric transport means such as an overhead gantry crane (be it magnetic or not), cranes and small forklifts we have:

$$C_{PON} = \left[\underbrace{(n_{ot} \times S_{ot} \times h_t)}_{Labour} + \underbrace{(K_e \times P_e \times h_t)}_{Electricity} + \underbrace{(C_d \times h_t)}_{Depreciation} \right] \text{ [€]} \tag{9}$$

n_{ot} – Number of transport workers [M]

S_{ot} – Transport worker wage [€/Mh]

h_t – Transportation time [h]

Transport means moved by fossil fuels as shipyard transporters (dollies), mobile cranes, floating cranes and forklifts, have the share of fuel costs replacing the electrical costs:

$$C_{VEI} = \left[\underbrace{(n_{ot} \times S_{ot} \times h_t)}_{Labour} + \underbrace{(K_C \times P_C \times h_t)}_{Fuel} + \underbrace{(C_d \times h_t)}_{Depreciation} \right] \text{ [€]} \tag{10}$$

K_C – Fuel consumption [l/h]

P_C – Fuel price [€/l]

These costs will be estimated relatively to the produced weight of steel variable in a simplified manner by the following equation:

$$C_t = P_b \cdot (\gamma_b \cdot CER_t \cdot MDO_t + CEQ_t) \text{ [€]} \tag{11}$$

CER_t – Transport cost estimate relationship [Mh/t]

MDO_t – Transport labour cost [€/Mh]

CEQ_t – Transport equipment costs [€/t]

3.4 Forming Costs

The costs of forming are dependent on the used forming equipment cost (purchase/rental, amortization, leasing, depreciation, maintenance, etc.), workers labor costs, and energy costs.

In the case of operations with the use of a roller press we have:

$$C_{CAL} = \left[\underbrace{(n_{oe} \times S_{oe} \times h_e)}_{Labour} + \underbrace{(K_e \times P_e \times h_e)}_{Electricity} + \underbrace{(C_d \times h_e)}_{Depreciation} \right] \text{ [€]} \tag{12}$$

n_{oe} – Number of forming workers [M]

S_{oe} – Forming worker wage [€/h]

h_e – Forming time [h]

In forming operations through heat distribution using multi-flame torches the electrical costs parcel is removed and substituted by a gas costs parcel:

$$C_{MAÇ} = \begin{bmatrix} \underbrace{(n_{oe} \times S_{oe} \times h_e)}_{Labour} + \underbrace{(K_O \times P_O \times h_e)}_{Oxygen} + \\ + \underbrace{(K_A \times P_A \times h_e)}_{Acetylene} + \underbrace{(C_d \times h_e)}_{Depreciation} \end{bmatrix} \text{ [€]} \quad (13)$$

Finally, one has the costs for the use of a portal press for shell plates forming:

$$C_{PSA} = \left[\underbrace{(n_{oe} \times S_{oe} \times h_e)}_{Labour} + \underbrace{(K_e \times P_e \times h_e)}_{Electricity} + \underbrace{(C_d \times h_e)}_{Depreciation} \right] \text{ [€]} \quad (14)$$

The cost equation for the stiffeners bending press will be identical to eq. (14).

These costs will be estimated according to the weight amount of processed steel in the following simplified equation:

$$C_e = P_b \cdot (\gamma_b \cdot CER_e \cdot MDO_e + CC_e + CEQ_e) \text{ [€]} \quad (15)$$

CER_e – Forming cost estimate relationship [Mh/t]

MDO_e – Forming labor cost [€/Mh]

CC_e – Forming consumables cost [€/t]

CEQ_e – Forming equipment costs [€/t]

3.5 Assembly Costs

Assembly costs are dependent on the number of assembling workers (labor costs), the used assembly equipment cost, consumables and energy costs.

$$C_{MON} = \begin{bmatrix} \underbrace{(n_m \times S_m \times h_m)}_{Labour} + \underbrace{(K_e \times P_e \times h_s)}_{Electricity} + \\ + \underbrace{(K_{ele} \times d_{sol} \times P_{ele})}_{Coated\ electrode} + \underbrace{(C_d \times h_s)}_{Depreciation} \end{bmatrix} \text{ [€]} \quad (16)$$

n_m – Number of marine assemblers [M]

S_m – Marine assembler wage [€/Mh]

h_m – Assembly time [h]

h_s – Welding time [h]

K_{ele} – Coated electrodes consumption [kg/m]

d_{sol} – Weld length [m]

P_{ele} – Coated electrodes cost [€/kg]

These costs will be estimated once again according to the variable of steel weight to be produced in the following equation:

$$C_m = P_b \cdot (\gamma_b \cdot CER_m \cdot MDO_m + CC_s + CEQ_m) \text{ [€]} \quad (17)$$

CER_m – Assembly cost estimate relationship [Mh/t]

MDO_m – Assembly labor cost [€/Mh]

CC_s – Welding consumables cost [€/t]

CEQ_m – Assembly equipment costs [€/t]

3.6 Welding Costs

The welding costs are dependent on the welding machines costs (purchase/rental, leasing, devaluation, and maintenance), welding speed (associated with consumption), number of welders (training and labor costs), cost of consumables and energy costs.

The cost of submerged arc welding (SAW) is:

$$C_{SAW} = \begin{bmatrix} \underbrace{(n_s \times S_s \times h_s)}_{Labour} + \underbrace{(K_e \times P_e \times h_s)}_{Electricity} + \\ + \underbrace{\left(K_{fio} \times d_{sol} \times P_{fio}\right)}_{Filler\ metal} + \\ + \underbrace{\left(K_{flu} \times d_{sol} \times P_{flu}\right)}_{Protection\ flux} + \underbrace{(C_d \times h_s)}_{Depreciation} \end{bmatrix} [€] \quad (18)$$

n_s – Number of welders [M]

S_s – Welder wage [€/Mh]

K_{fio} – Cored wires consumption [kg/m]

K_{flu} – Protection flux consumption [kg/m]

P_{fio} – Cored wires price [€/kg]

P_{flu} – Protection flux price [€/kg]

Note that it might be taken into consideration, that a part of the flux protection can be reused.

Regarding the use of flux-cored arc welding (FCAW) with gas protection have the following costs:

$$C_{FCAW} = \begin{bmatrix} \underbrace{(n_s \times S_s \times h_s)}_{Labour} + \underbrace{(K_e \times P_e \times h_s)}_{Electricity} + \\ + \underbrace{\left(K_{fio} \times d_{sol} \times P_{fio}\right)}_{Filler\ Metal} + \\ + \underbrace{\left(K_{pro} \times d_{sol} \times P_{pro}\right)}_{Protection\ Gas} + \underbrace{(C_d \times h_s)}_{Depreciation} \end{bmatrix} [€] \quad (19)$$

K_{pro} – Protection gas consumption [kg or m^3/m]

P_{pro} – Protection gas price [€/kg or m^3]

Finally, one has the use of SMAW welding with coated electrodes that is very similar to eq. (16) only replacing in the labor cost parcel the assembly time by welding time:

$$C_{ELE} = \begin{bmatrix} \underbrace{(n_s \times S_s \times h_s)}_{Labour} + \underbrace{(K_e \times P_e \times h_s)}_{Electricity} + \\ + \underbrace{(K_{ele} \times d_{sol} \times P_{ele})}_{Coated\ Electrode} + \underbrace{(C_d \times h_s)}_{Depreciation} \end{bmatrix} [€] \quad (20)$$

These costs will be estimated for the produced weight of steel in the simplified equation:

$$C_s = P_b \cdot (\gamma_b \cdot CER_s \cdot MDO_s + CC_s + CEQ_s)\ [€] \quad (21)$$

CER_s – Welding cost estimate relationship [Mh/t]

MDO_s – Welding labor cost [€/Mh]

CEQ_s – Welding equipment costs [€/t]

Other costs to be consider, but not analyzed in the present study, may be the environmental costs, dimensional control and quality costs, inspection and certification costs, additional work or reworks costs.

In summary, the overall simplified cost for the construction of a ship steel hull is therefore equal to the sum of the costs of all cost centers discussed above, adding an extra parcel related to the costs not analyzed in this study.

$$C_{TOTAL} = C_p + C_c + C_t + C_e + C_{\mathrm{m}} + C_s + C_{EXTRAS}\ [€] \quad (22)$$

The cutting and welding activities are normally those that consume more man-hours and depending on the used technology it can lead to significant non-productive costs [20].

The cost structure of ship repair is far more complex than the construction, because there are many more factors and details to consider. The budgeting of repair requires a detailed analysis of each work to be performed aboard ship or in a workshop [21] and it requires this usually in a very short time period.

4. First Case Study

The first case analyses the work preparation, cutting and forming processes that will be employed in the shipbuilding of three hopper barges made by MPG Shipyards in association with One Ocean (OCE) design office.

These hopper barges are 85 meters in overall length, with a breadth of 15 meters and approximately 5500 tons (maximum loaded displacement).

Fig. 1 illustrates the blocks being built by the company in question and its relative position along the vessel.

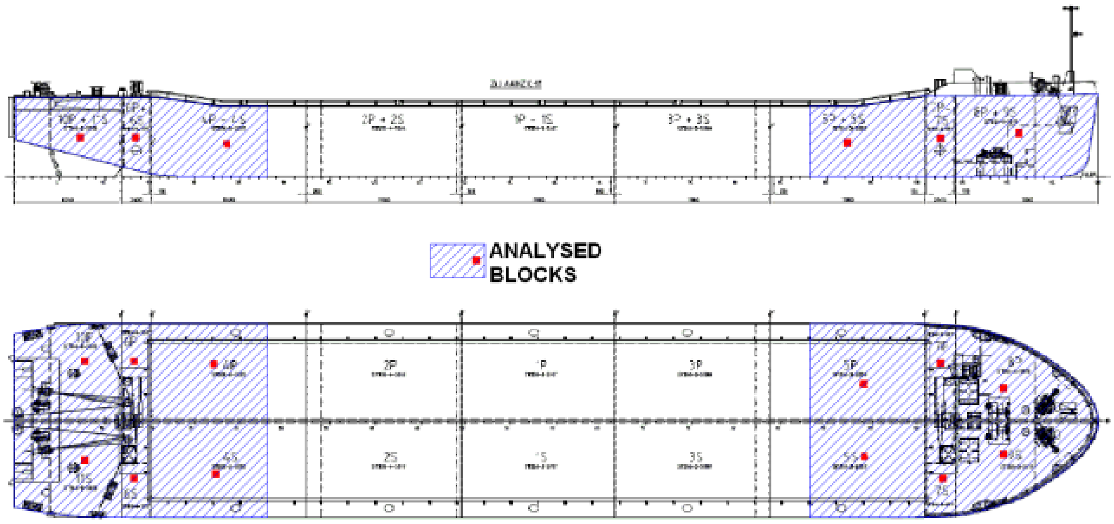


Fig. 1 Hopper Barge analyzed blocks

4.1 Work preparation processes

Marine design bureau OCE was in charge of the cutting work preparation. The cut preparation starts by a careful analysis of the shipyard submitted ship plans.

The work preparation process involves part modelling in CAD software tools such as AutoCAD and DEFCAR, being the latter the most important for cutting settings and specific details. AutoCAD is used after DEFCAR because it provides a better graphical visualization of the 3D model created, allowing a better validation of the cut parts and check for possible interference and non-conformities. In addition to that it also helps the issuing of assembly drawings, stiffeners cutting/bending drawings and "As built" ship plans.

Table 2 shows the time spent on work preparation for the cut of 360 tons of steel, comprising 2033 parts and 669 stiffeners.

Table 2 Spent work preparation time by performed task

Task	Time [h]	[%]
DEFCAR parts modelation	483	28
AUTOCAD 3D modelation	660	39
LANTEK cutting files generation	318	19
Production, assembly & forming drawings	245	14
TOTAL	1706	100

This gives an estimate work preparation cost of 5 hours per ton of processed steel. It is interesting to note that, in general, the work preparation costs are only referring to the first vessel built, and if there are more sister's vessels to be built that does not increase this shipbuilding cost parcel. However, sometimes there are extra costs associated with preparation and design, which are related to royalties (rights over work replication) to be paid accordingly to the number of units to be built.

$$Final\ Price = C \cdot \sum_{i=1}^{n} \frac{1}{n} \tag{23}$$

C is the work cost of one unit and *n* is the number of units to be constructed. It is useful to have in mind that the project cost of a new ship ranges in values of 3 to 10% of the total ship cost, and the engineering design and production details may involve 5 to 15 % of all direct labour hours of construction [22].

After OCE generated all the necessary parts to build the ship it uses suitable software to make the nesting of all of the pieces to fit in standard steel plates. Finally, it creates CNC files, which are basically orders understood by the plasma-cutting machine for each one of the nesting jobs.

From the 136 steel plates with associated analysed nesting, it is possible to observe an average use of 75% of the plate. Thus the remaining 25% of plate may be considered waste and must therefore be taken into account as an additional cost to the overall building cost. Part of this wasted steel may be sold as scrap, returning its residual value and slightly decreasing costs. The scrap prices average € 0.08 to € 0.10 per kg (depending heavily on the steel price which is linked to global economic factors, such as the oil prices increase and growing demand in Asia). Some sources put the steel scrap price at $ 120 / ton [23].

4.2 Cutting processes

The initial estimate provided by the MPG shipyard gives a ratio of 3 tons of processed steel per hour; which includes cutting, marking and transportation of parts (0.33 hours/ton). The estimate of 0.5 hours/ton is more appropriate if edge grinding is also included.

The shipyard also estimates that the operational costs are 0.15 €/kg or €150 for each ton of steel.

The analysed blocks of this study are presented in Table 3.

Table 3 Total steel weight of the analyzed blocks

Location	Blocks	Weight [t]
Bow	7P+7S+8P+9S	127
Stern	6P+6S+10+11S	125
Midship	5P+5S+4P+4S	108
	TOTAL	360

$$HT = CER_{proc} \times \sum_{i=0}^{n} Pb_i \tag{24}$$

HT = Required number of hours for steel processing

CER_{proc} = Cost estimate relationship of time per weight of processed steel

Pb = Block weight

Using the equation (24) it would take about 180 working hours or four weeks of work to cut 360 tons of steel with a CER_{proc} of 0.5 Mh/t.

Regarding the cost for this cutting work, considering the 150€/t CER and using eq. (3), the final break-even work cost is about € 54,000.

$$C_{cutting} = CER_{cut} \times \sum_{i=0}^{n} Pb_i \quad (25)$$

CER_{cut} = Cost estimate relationship of price per weight of processed steel

The relationship between plate's thickness and recommended plasma cutting speed is illustrated in Table 4.

Table 4 Cutting speed according to plate thickness

Plate Thickness [mm]	6 to 7	8 to 9	10 to 11	12 to 13	14 to 16	17 to 20
Cutting Speed [cm/min.]	340	300	240	200	140	90

For thicknesses exceeding 20 mm the cut is performed with automatic oxycut. For 20 mm thickness the recommended speed is 40 cm/min and for 300 mm thickness plates the velocity is 17 cm/min. For intermediate values of thickness it is reasonable to make an approach speed value that is inversely proportional to thickness.

Other observed speeds for this cutting machine are the positioning speed (plasma or oxy-cutting nozzle movements along the plate without performing the actual cut) and the plate marking speed. In the first case we have a speed of 1500 cm/min, and the latter we have 1000 cm/min.

It was analysed the cutting of 5 plates with different numbers of parts to be cut and with several thicknesses (implying different cutting speeds) described in Table 5. One of the cases uses the oxycut nozzle instead of the plasma.

Table 5 General characteristics of the 5 analyzed cut plates

Plate			Cutting Machine		Nesting	
ID	Type	Thickness	Method	Speed	Nr. of Parts	Cutting Perimeter
648	Steel	8 mm	Plasma	295 cm/min	14	130 m
021	Steel	12 mm	Plasma	200 cm/min	7	70 m
015	Steel	12 mm	Plasma	200 cm/min	31	87 m
004	Steel	8 mm	Plasma	295 cm/min	53	132 m
267	Steel	30 mm	Oxycut	40 cm/min	2	44 m

Table 6 shows the time spent on each cutting task.

In the case of plate 267 it is noticeable that about 50% of the time is spent in zone pre-heating before the actual cutting of the lap welding holes starts. This means that from the 106 minutes openings cutting time roughly 54 minutes are spent on pre-heating the plate locally. This happens because in this case it is used the oxycut method.

Table 6 Spent time according to cutting task

Action	Spent Time [minutes]				
	Plate 648	Plate 021	Plate 015	Plate 004	Plate 267
Plate transportation to cutting table	6	5	3	4	6
Cutting file loading and validation	3	2	2	3	2
Cutting head alignment	3	2	2	2	2
Cut (ref. marks on plate)	8	11	20	4	0
Cut (openings)	4	3	0	3	106
Cut (Parts contours)	47	31	49	42	65
Parts paint marking	7	5	7	11	1
Plate transportation to cutted plates park	5	5	3	5	3
TOTAL	83	64	86	74	185

Table 7 illustrates the differences between the estimated cutting time values using the known theoretical cutting, marking and positioning speeds and the actual cutting time values obtained.

Table 8 summarizes the 360 cut steel tonnes work performed by the shipyard. Only about 75% of the steel plate is used for parts generation, the remaining 25% of wasted material can be reused for small parts cutting or sold as scrap.

Table 7 Comparison between estimated and actual cut time

	Cutting Time [min.]		
	Estimated	Real	Error [%]
Plate 648	50	59	15
Plate 021	43	45	4
Plate 015	54	69	22
Plate 004	46	49	6
Plate 267	120	171	30

Table 8 360 ton steel cutting summary

	Nr. of parts	Perimeter [m]			Weight [Kg]			Area [m^2]	Time [min.]
		Marking	Cutting	Positioning	Plate	Cutted Parts	Efficiency	Cutted Parts	Total Cut
BOW	828	1758	3720	1559	174236	126586	72.7	1144	2855
STERN	765	2014	3435	1604	171591	124740	72.7	1109	2705
MIDSHIP	440	2354	2591	1312	138219	107798	87.8	913	1920
TOTAL	2033	6127	9746	4475	484046	359125	74.2	3166	7480

Fig. 2 shows through a pie chart the percentage of spent time according to task performed by the cutting machine.

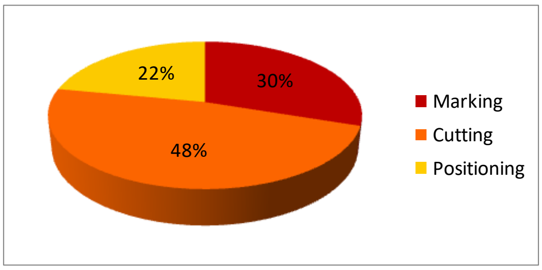


Fig. 2 Distribution of spent cutting machine time for the block parts

It is possible to conclude that 22% of the total time spent by the cutting machine is related to cutting nozzle positioning movements, 30% with plate markings and finally 48% of the time is spent in actual parts cutting. This means that only half of the operating time of the cutting machine correspond to effective cut.

Now to obtain the final spent time of this cutting job it is necessary to add all the times spent on tasks such as the plates transporting, the cutting machine calibrations, the parts identification, the cutting of parts plate joints and the parts edge grinding and polishing.

In order to estimate the time spent on other cutting tasks it was analised a set of 135 plates that have generate 2033 parts obtain with the cut with a total length of the cutting of 9745m. In accordance with corresponding observed average task speed, it will allow to calculate the spent time as presented in Table 9.

Adding up now all the spent work time one gets a final time of 44,863 minutes or 748 hours to cut 360 tons of steel.

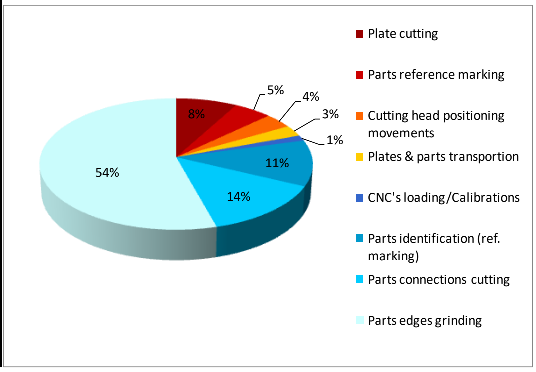
Table 10 presents the time distribution for each associated cutting task by means of pie chart. It is easily understood why MPG assigns, in average, three men for parts edge grinding duties, thus reducing drastically the largest slice of spent time on the cutting process.

Table 9 Task list associated with the cutting process

	Average Speed	Spent Time [min.]
Plates & parts transportion	9 min/plate	1224
CNC's loading/Calibrations	4,5 min/plate	612
Parts identification (ref. marking)	2,5 part/min	5082.5
Parts connections cutting	3 part/min	6099
Parts edges grinding	0,4 m/min	24365

Table 10 Total cutting time of the analyzed cut job

Process	Spent Time [min.]
Plate cutting	3590
Parts reference marking	2244
Cutting head positioning movements	1646
Plates & parts transportion	1224
CNC's loading/Calibrations	612
Parts identification (ref. marking)	5083
Parts connections cutting	6099
Parts edges grinding	24365
TOTAL	44863



4.3 Forming processes

It was analysed the forming process of two 20mm plates located in the bow of the ship.

The first plate 1000-9S (Fig. 3), located at the forward bilge part of the bow, has a total forming time of 72 Mh distributed as follows: one 6 hours shift with two operators for basic forming in the roller press, three 8 hour shifts with two workers equipped with heating torches to perform heat deformations and finally a single shift of six hours with two operators for the final plate forming on the portal press.

Fig. 3 Plate 1000-9s

Fig. 4 Plate 696-7S

The second plate 696-7S (Fig. 4), has substantially less forming time of 24 Mh distributed as follows: 1 shift of 6 hours with two operators for basic forming in the roller press and a six hours shift with two operators for the final forming on the portal press.

Fig. 5 Basic forming of amidships bilge plate

Regarding bilge shell plates amidships (Fig. 5), it was concluded that it would be spent 12 Mh (depending on the size of the plate) since it only requires the use of the roller press for basic plate forming which represents one 6 hour shift with two workers.

Passing now to the time analysis of stiffeners bending by means of an electro-hydraulic press it was noticed that a reinforcement profile HP140x7, 3 meters long, with a slight curvature took about 20 minutes to be shaped involving a team of two men.

Fig. 6 illustrates the hopper barge floating in shipyard dock after construction.

Fig. 6 Hopper barge baptism at Lisnave's dry dock

5. Second Case Study

This case study analyses the assembly, transport and welding processes of several blocks built by Joperinox Shipyards in association with OCE design office. These blocks will be delivery via sea to their final assembly destination in Astilleros Armon shipyards (Spain) where they will be joined to form a 79.2 m LOA, 15 m beam, 6.5 m draft and 1390 t displacement fisheries support vessel. Fig. 7 illustrates the 11 blocks to be built by Joperinox shipyard.

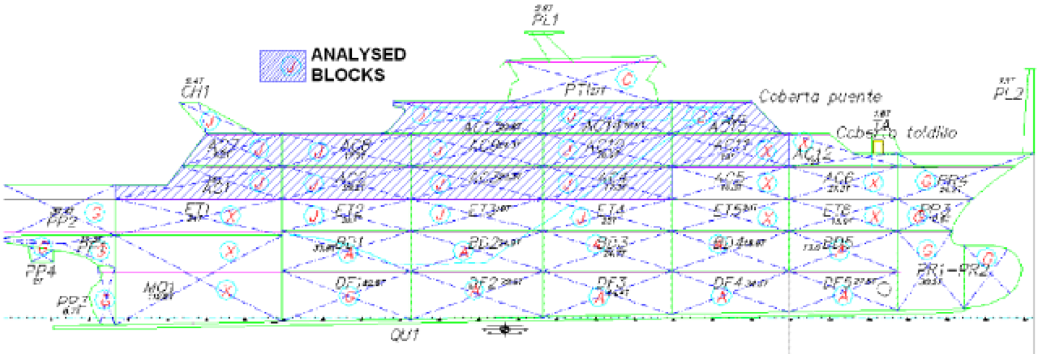


Fig. 7 Analyzed Superstructure blocks

5.1 Assembling and welding processes

Teams of two workers make the assembly. Usually a more experienced worker teams up with a trainee or lesser-experienced worker in order teach the craft.

Welding is carried out individually. Each welder is responsible for its own welding machine and for the completion of a given work plan.

In this study it is considered two types of weld joint, T joints and butt joints. Relatively to the type of fillet there were double fillet welding (continuous) and staggered intermittent welding (discontinuous) on T joints. The butt joints were all continuous fillet.

The discontinuous welds will reduce the spending on consumables, man-hours and energy, as well as a significant weight decrease in each block. This type of welding should always be applied in all parts unions that do not compromise the structural integrity of the ship.

The deck plate’s butt-joint unions are made with submerged arc welding. Other structural components unions such as beams, frames, stiffeners and bulkheads use flux-cored welding with gas protection. The SMAW is only used in assembly tasks where it is required temporary parts unions with some weld drops.

Now taking in account the amount of deposited weld [24, 25], in practice we have: 500g to 600g per meter in continuous T joint welding (counting on both sides), 130g to 160g per meter in discontinuous T joint welding (counting both sides), and finally 500g/m in the continuous butt joint welding (taking into account average plate thickness of 7 mm).

Joperinox shipyard estimates a required 50 man-hours for each ton of processed steel, which includes the assembly, welding, grinding and polishing.

To estimate the number of hours (HT) that will be required it is used again equation (2). The weights of the 11 blocks considered in this study are shown in Table 15 and in total they weigh 204.8 tons. Having said that, it would take 10240 man-hours to complete all of them as result of HT = 50 x 204.8 = 10240 Mh.

It was measured the assembly time of 20 stiffeners (HP140x8 mm profiles) on the deck of block AC03. Each profile has about 10 m of length with a combined total weight of 2240 kg. An initial estimate approach may consider the use of equation (2), which leads to 112 man-hours required, HT = 50 x 2.24 = 112 Mh.

Table 11 illustrates the times that each operation took, which involved four assemblers and two welders.

Table 11 Stiffeners assembly times and associated manpower

		Assembling & Welding of 20 profiles with 12m each on Block's AC03 deck			
		Status	Team (M)	Time (min)	Mh
1st Day	Morning	All clips placed	2	200	7
	Afternoon	6 profiles placed & 2 profiles fixed with drop weld	2	275	9
2nd Day	Morning	2 profiles placed & 8 profiles fixed with drop weld	4	275	18
	Afternoon	2 profiles placed & 15 profiles fixed with drop weld	4	275	18
3rd Day	Morning	17 profiles fixed with drop weld & 3 welded profiles	6	275	28
	Afternoon	20 welded profiles	2	275	9
			Total hours	26.25	89

It was observed that in reality it was necessary 89 Mh to finalize this process. A value that despite being lower than the initial estimates it is closer, which proves that the estimated 50 Mh/t is somehow adjusted. Fig. 8 shows the percentage of work completion over the 26 hours of the total working time.

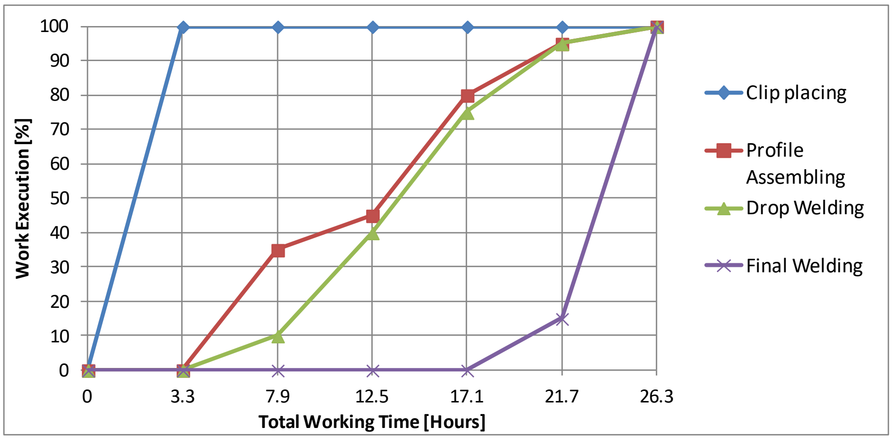


Fig. 8 Assembly execution percentage for 20 stiffeners

Fig. 9 presents the spent time by task distribution. Note that it was used discontinuous manual FCAW in this particular welding job.

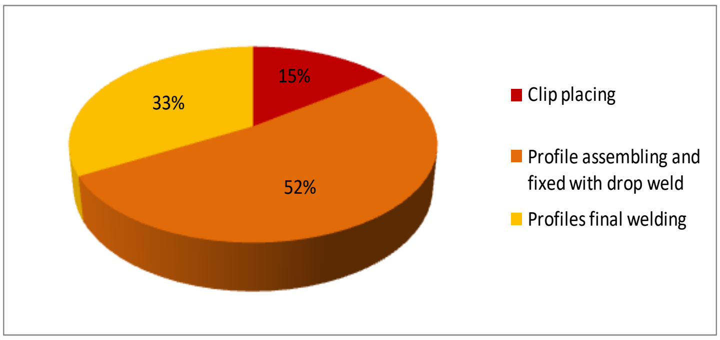


Fig. 9 Assembly time distribution for 20 stiffeners

Table 12 presents the average speeds recorded for each assembly and welding task.

Table 12 Average speed for each task

Process	Speed [m/h]
Submerged arc welding (7mm thickness)	13.4
Fluxed core manual continous welding	2.8
Robot fluxed core automatic continous welding	20.0
Fluxed core manual discontinous welding	22.2
Drop welding using coated electrodes	incl. In assembly
Reinforcement profiles assembly	2.4

The FCAW welding speed observed can be compared with data provided by the shipyard from previous welding works and presented in Table 13.

Table 13 Speeds of several welders using FCAW with gas protection

Welder	A	B	C	D	E	F	G	H	I	J	K	Average
Speed [m/h]	2.29	1.21	1.64	3.80	3.37	2.23	4.14	1.86	1.54	1.83	2.16	2.37

This study involved the 3D generation of 11 blocks similar to the one in Fig. 10.

These 3D models are used to obtain several information such as: the number of plates and associated stiffeners; total lengths of assembled stiffeners; total and partial welding lengths in plates and stiffeners (taking into account the use of two different welding technologies) and assembly complexity.

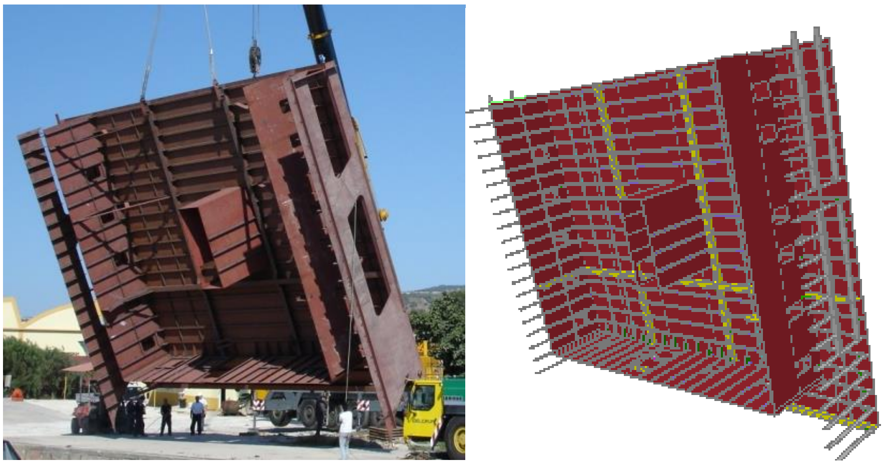


Fig. 10 Block AC13 vs. 3D model

From the obtained data it was carried out a relationship study between various components in the construction, in particular the amount of linear welding vs. block weight and the number of stiffeners vs. block's weight (Table 14).

Table 14 Blocks weight and associated welding length

Bloco	Weight [ton]	Continuous Welding Lenght [m]	Descontinuous Welding Lenght [m]	Total Welding Lenght [m]	Number of profile reinforcements
AC01	15	254	85	339	64
AC02	28.2	592	276	868	112
AC03	22.3	418	328	746	81
AC04	17.3	341	226	566	28
AC07	4.2	103	27	130	21
AC08	17.7	450	105	555	145
AC09	24.3	549	249	799	153
AC10	20.9	513	219	732	84
AC13	22.8	574	298	871	304
AC14	18.9	551	207	758	238
AC15	13.2	350	200	550	174
Total	204.8	4695	2219	6914	1404

Based on these values it is possible to obtain various linear regressions in order to find the equations for calculating approximate welding lengths shown on Fig. 11.

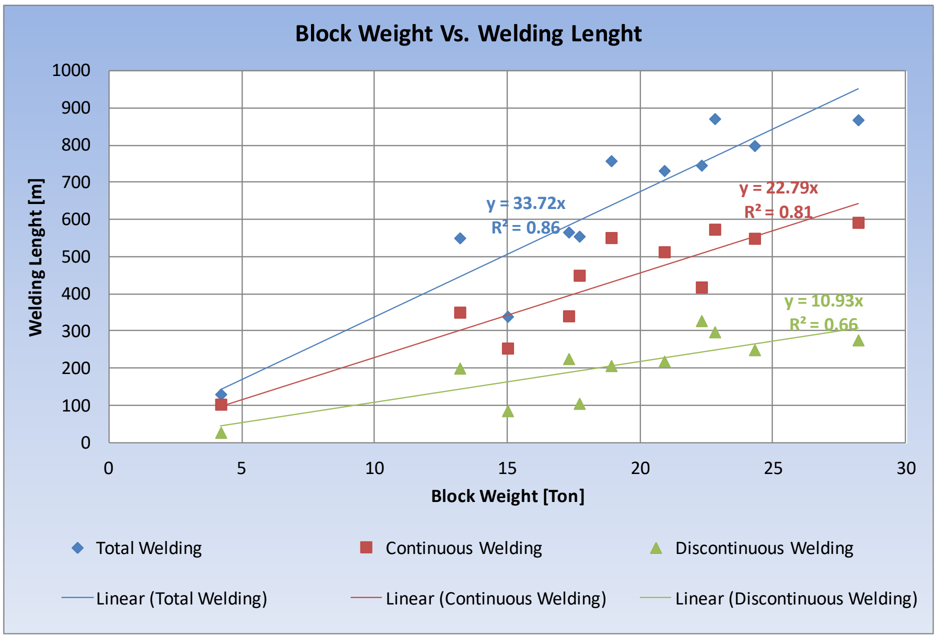


Fig. 11 Blocks Weight vs. Welding length

This analysis establishes relations between the welding length and weight of the block, P_b, by the following equations:

$$L_{Total\ Welding} = 33{,}7 \cdot P_b \ [\mathrm{m}] \tag{26}$$

$$L_{Continuous\ Welding} = 22{,}8 \cdot P_b \ [\mathrm{m}] \tag{27}$$

$$L_{Intermittent\ Welding} = 10{,}9 \cdot P_b \ [\mathrm{m}] \tag{28}$$

It was found a very interesting value on this quick analysis which has been called factor λ. This factor corresponds to the division of LWHW (Multiplication of block's length, width, height, and weight) by the total welding length.

Table 15 Main dimensions of the blocks built by Joperinox

Block	Lenght [m]	Width [m]	Height [m]	Weight [t]	LxWxHxW	Weld Lenght [m]	l Factor	
AC01	5.9	7	2.5	15	1548.75	339	4.6	X
AC02	8.6	15	2.5	28.2	9094.5	868	10.5	
AC03	10.2	15	2.5	22.3	8529.75	746	11.4	
AC04	10	15	2.5	17.3	6487.5	567	11.4	
AC07	5.9	2.9	2.5	4.2	179.655	130	1.4	X
AC08	9.9	15	2.5	17.7	6571.125	555	11.8	
AC09	10.2	15	2.5	24.3	9294.75	798	11.6	
AC10	10	15	2.5	20.9	7837.5	732	10.7	
AC13	11.6	15	2.5	22.8	9918	872	11.4	
AC14	9.9	15	2.5	18.9	7016.625	758	9.3	
AC15	6.2	15	2.5	13.2	3069	550	5.6	X
						Average	11.0	

If the particular cases of small blocks AC01 and AC07, and also block AC15 are removed, the average value of λ is 11 (Table 15).

The factor λ allows the verification whether the dimensions of given block are within the boundaries of this study analyzed blocks. Moreover λ factor allows the estimation of the weight of steel in each block at a very preliminary ship design level, where there is only the division of blocks, which provide overall dimensions and weld lengths provided by the amount of existent stiffeners. Table 16 presents the distribution of used type of welding process.

Table 16 Welding type usage distribution

Block	SAW [m]	FCAW [m]	SAW [%]	FCAW [%]
AC01	15	324	4	96
AC02	69	799	8	92
AC03	82	664	11	89
AC04	80	487	14	86
AC07	16	114	12	88
AC08	57	498	10	90
AC09	80	718	10	90
AC10	80	652	11	89
AC13	69	803	8	92
AC14	79	679	10	90
AC15	52	498	9	91
		Average	10	90

On average in vessel shipbuilding for each meter of submerged arc welding we have 9 meters of fluxed cored arc welding.

The consumables expenditures are shown in Table 17 and were calculated by the linear regressions equations shown in Fig. 11.

In summary it is spent 3.1 tons of welding addition material which corresponds roughly to 1.5% of the built steel weight (204 tons). It is a value lower than expected for the construction of a vessel, which is normally around 2% to 3% of the total weight. However, this study does not include the welding of the shell plates and the block's union, so the obtained percentage is acceptable.

Table 17 Flux cored wire reels expenditure

	Flux Cored Wire Expenditure			
Block	Butt Joint Welding (kg)	Continuously Fillet Joint (kg)	Discontinous Fillet Joint (kg)	Number of Reels (16 kg)
AC01	7.34	143.51	12.80	11
AC02	34.52	313.89	41.38	25
AC03	40.90	201.86	49.15	19
AC04	39.80	156.60	33.83	15
AC07	8.19	51.91	4.07	5
AC08	28.35	235.86	15.76	18
AC09	39.90	281.65	37.41	23
AC10	39.80	260.03	32.78	21
AC13	34.65	302.61	44.63	24
AC14	39.70	283.07	31.01	23
AC15	25.93	179.16	29.98	15
TOTAL	339.08	2410.17	332.80	199

Relatively to the spent welding reels (about 200) the value is within the expected, but it might be added 5% extra reels to account for the expected waste. Assuming that each reel is valued at € 38, the total cost of addition material acquisition would be € 7,600.

It is assumed that for each kilogram of deposited metal it is necessary to spend 4 kW [24]. So for the 3.1 tons of spent weld this would represent an expenditure of 12,800 kW. Considering an electricity price of € 0.10 / kW, we have a final cost of € 1,280.

If we take into account the estimated 10,240 Mh required for the completion of the 11 blocks and an average wage of all workers of € 8/Mh, we have labour cost of about € 82,000. Therefore the costs with electricity and consumable materials represent 10% to 11% of the labour cost. These results demonstrate that the expenditure on consumable materials, electrical and protection gas costs have a residual cost when compared to the labour cost.

Through the 3D block models created for this study it is possible to know the total weight of stiffeners (HP profiles, L bars and flat bars) with good accuracy, which is roughly 39.2t of the total 11 blocks weight. That value suggests that about 20% of the weight of each block is associated with stiffeners. This percentage of stiffeners can be a good indicator to calculate the number of reinforcement profiles to be bought for a given block.

Fig. 12 shows the built ship beginning her sea trials.

Fig. 12 Fisheries support vessel at sea trials

6. Conclusions and recommendations

It is possible to divide the hull's manufacturing cost into 6 simplified parts, corresponding to different cost centers and through adjustment coefficients on the productivity of each process and complexity of implementing it, one can get corrected cost estimates.

Usually the naval architect/marine engineer, at the ship's design stage, focus only in the technical details of a new shipbuilding, without considering much the cost implications that each design solution can bring. However, engineers and architects recognized how important is the awareness of the economic implications of each choice they make in the ship's design phase. This process usually is refined according to the increase of individual experience and culminates with the seamless integration of technical structural solutions and best production practices. A production strategy that adopts both best shipbuilding and engineering practices, and takes into account the facilities, workforce and equipment of the shipyard can gain considerable competitiveness [26].

Shipbuilding productivity can attain considerable gains by taking in account aspects of production (DFP - Design for Production) [27]. Considering this point, any ship's design bureau should, wherever possible, follow ship design guidelines that take in account the aspects of production, preferably associated with the manufacturing methodology of a given shipyard, because what may be a great production advantage in a large shipyard with a large number of resources and technological capabilities, may not be in a small yard with limited resources. So DFP must be appropriate for each case, which is not always possible for an independent design office.

In order to increase the productivity of the yards LEAN manufacturing principles should be implemented [28]. These principles minimize waste in costs of materials and activities that do not add productive value, imply a constant improvement of methods and processes, the increase of relevant information sharing in order to improve quality and productivity and make all production processes flexible and open to new changes, so that they can be better adapted to new realities.

The profile cutting process should be an automated process to increase productivity. It could have a procedure similar to the plate cutting, in which there exists a table where profiles would be put and cut according to an automatic order given by CNC cutting files. In the plate cutting process it appears that the time spent in edge grinding and finishing processes of each cut steel part is an important variable to have in consideration and which has a heavy weight in the overall cutting costs.

The availability of data about steel hull's production on small shipyards is very scarce. The present study presents on site information about the production of steel in small shipyards. It includes data about the technological processes involved in terms of costs related to labour man-hours, consumables and auxiliary activities. Statistical analysis have been performed in order to achieve indicative parameters that may be applied in a cost analysis methodology.

Regarding the simplified formulas for calculating the costs for each production process described in this study, it appears that the most important variables are the labour costs and productivity associated with each process, which in turn is connected to the technology of the equipment used and the degree of qualification of the worker. The costs associated with supplies and equipment used in the production process are only a small portion of the total costs.

In the plate cutting process it appears that the time spent in edge grinding and finishing processes of each cut steel part is an important variable to have in consideration which has a heavy weight in the overall cutting costs.

In relation to the means of transportation, it is of utmost importance for a productive shipyard, which builds vessels in steel, to be equipped with magnetic crane. The use of forklifts is not a practical and effective way of subassemblies transportation and it should only be used for equipment, materials and supplies transportation. Gantry cranes will always be the key elements in moving blocks, however the use of rented truck cranes, although expensive, is always a good solution for smaller yards that do not have the resources, long-term strategic or portfolio of new constructions, to justify the purchase of expensive means of movement.

The use of robots for welding reinforcements on horizontal panels is an important feature in any efficient and competitive shipyard. The use of this type of welding allows a reduction of at least three times the welding time and cost of manpower in the welding of small reinforcements (up to 2 meters). For larger panels with longer reinforcements the gain on reducing the execution time and cost of skilled labour is even greater. The manual welding should therefore be reduced to what is strictly necessary, such as: union of bulkheads, interrupted structural elements, upwards welding, vertical welding, blocks joints, hull shell seams, etc. The discontinuous fillet welding should always be used where permitted, in order to save time, costs in supplies and manpower.

As final conclusion, the presented manufacturing cost estimate methodology may be easily implemented in each particular shipyard by collecting data directly from production, as demonstrated in the case studies presented. It allows to estimate the CER for each formula and then to quantify the importance of each activity in terms of the impact in the total cost of the production. The analysis of such information allows to make changes in the production in order to reduce costs and eventually to compare the performance of production of the shipyard with similar shipyards.

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