Model to Forecast Times and Costs of Cutting, Assembling and Welding Stages of Construction of Ship Blocks

A. Oliveira & J.M. Gordo
Instituto Superior Técnico, Universidade de Lisboa, Portugal

ABSTRACT: The international competition in shipbuilding is a subject that weighs heavily in new ships orders and leads to the study about the feasibility of adopting new technologies and processes in the production flow, in order to respond to the current challenges. Thus, a program was developed to forecast times and costs in the construction processes stages of ship blocks in a shipbuilding yard, allowing the simulation of implementation of alternative cutting and welding technologies. The main goal of this study is to understand the relation between operational and labor costs in various types of cutting and welding technologies, and the potential earnings related to cost savings in downstream stages of the production flow due to the application of higher quality technologies in upstream processes. The times and cost values computed by the developed algorithm grant a deeper understanding of the consequences of the adoption of alternative shipbuilding technologies in the productive process.

1 INTRODUCTION

The construction by blocks is the most reliable production scheme in a construction shipyard in order to achieve a more cost-effective production, with simultaneous increase on the quality of the processes, and is vastly accepted that is undoubtedly the today's mainstream scheme of ship construction (Storch, et al., 2007).

The block construction is today a well-defined sequence of stages, according with the type and characteristics of the block, as illustrated in Figure 1.

It is important to stress that in the present study the pre-outfitting activities of the block were not considered, although they are an important strategy to contribute to a more cost-effective production process.

For each stage of the sequence shown in Figure 1 there is a different set of available technologies and techniques. One can exemplify with the current available technologies for the cutting process. Either for the steel plate or for the frames cutting stage, different possibilities are currently available: Oxy-fuel cutting, plasma cutting, laser cutting and abrasive water-jet cutting (Oliveira & Gordo, 2018). The same principles apply for example on the several structural levels, from small complex pieces to final block construction stage, where many different welding techniques can be used, from electrodes to the newest welding technologies, such as laser beam welding or plasma welding (Gordo, et al., 2006).

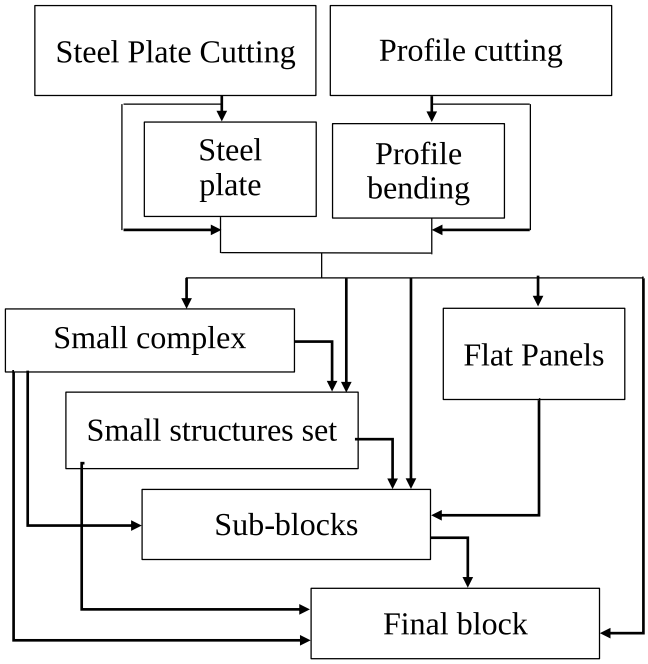
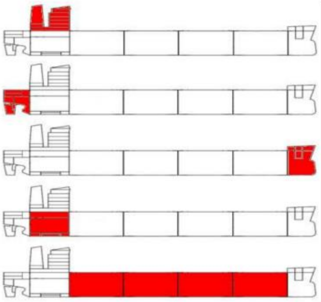


Figure 1 Block production sequence main stages scheme

In way to understand the implications of the implementation of different options of cutting and welding technologies in the block construction flow process, several studies were conducted to analyze the consequences of the variation of the production's time and cost parameters (Leal & Gordo, 2017). Also, by implementing and developing simulation tools, other set of studies were conducted to obtain a better understanding of the production flow when faced with different production options (Ljubenkov, et al., 2008)

(Oliveira & Gordo, 2018). In this way, several studies have proved gains in the construction process, for example in double bottom blocks (Ozkok & Helvacioglu, 2013). Also, by applying lean tools, several studies had proven positive results on the manufacturing processes (Kolich, et al., 2016), hence stressing the importance for a careful manufacturing planning.

In way to obtain a reliable set of results on the construction process, it is important to specify as well as possible, not only the production process, like cutting or welding processes, but also the block that is being analyzed. For the understanding of one of the present study's main goals, it is key to realize that in many past parametric studies on the block production process, the block is characterized only by a small set of values, according with the block type and dimensions, as shown in the Figure 2:



Complexity Coefficient	
Superstructure	1,00
Bow	1,35
Bow (with Bulb)	1,45
Stern	1,35
Stern (with *Skeg*)	1,45
Engine Room	1,50
Midship	1,10
Midship (Double Bottom)	1,25
Midship (Double Side)	1.25

Figure 2 – Block complexity coefficient. (Leal & Gordo, 2017)

The present study aims to avoid the use of the above values shown in Figure 2, by developing a model where the user set the characteristics of the production process and a deeper characterization of the block which production cost and times one wants to analyze.

2 PRODUCTION ANALYSIS MODEL

2.1 *Data flow*

The developed model aims to conduct a more reliable analysis of the production process of the block in the shipbuilding yard, and for that one of the key features is the consideration of all the steel pieces which form the block.

Through a set of graphic interfaces, the user should be able to define the block's pieces, as also the shipyard processes specifications. Hence, as shown in Figure 3, the model's input arguments are the block's pieces characteristics and the production process specification. Through a series of computations, the model creates automatically a set of *PDF* files with the times and costs of the main construction stages, as well as a *Microsoft Project* file with the flow production.

The characterization stage of the block's pieces is realized through the Rhinoceros CAD program. According with a standardized way of definition of the characteristics of each block piece, the user defines those characteristics in the Rhinoceros program. The characteristics defined by the user are divided in several values which comprehend values that deal with:

- Piece type;
- Piece dimensions;
- Lengths of cutting and welding;
- Level of possible bending;
- Stage of block construction to which belongs.

The main menu of the developed model presents an option that allows to update the Rhinoceros file with a different block or with an actualized block pieces' characteristic.

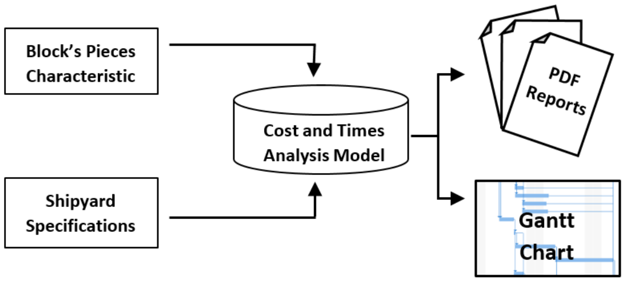


Figure 3 – Model data flow

Figure 4 – Main menu model's graphic interface.

The shipyard block construction processes specifications are defined by the user through a set of graphic interfaces of the developed software. The production specifications are divided in the following sets of data input, each one with their own graphic interfaces:

Cutting Processes
- Profiles Cutting
- Steel Plates Cutting

Forming Processes
- Profiles Bending
- Steel Plates Bending
- Steel Plates Forming

Assembly and Welding Processes
- Small Complex Pieces
- Small Structures
- Flat Panels
- Sub-blocks
- Final Block

The data defined in each of the production stages presented above is related with the process type, but can be summarized in the following set of values:

- Process speeds and times;
- Technologies used;
- Number of active workstations;
- Number of workers needed.

In the shipyard specification phase of the values input activities is also included the specification of the costs of the several processes, according with the type of technology and equipment used, as shown in the Figure 5.

The costs definition also depends strongly on the type of technology and equipment one is defining, but can also be summarized in the following set of values:

- Consumables flow rate;
- Electricity consumption;
- Equipment Depreciation;
- Wage of the technician worker.

For a more reliable construction process analysis, the user should also define the production flow of the several structures levels that made up the block, as shown in Figure 6.

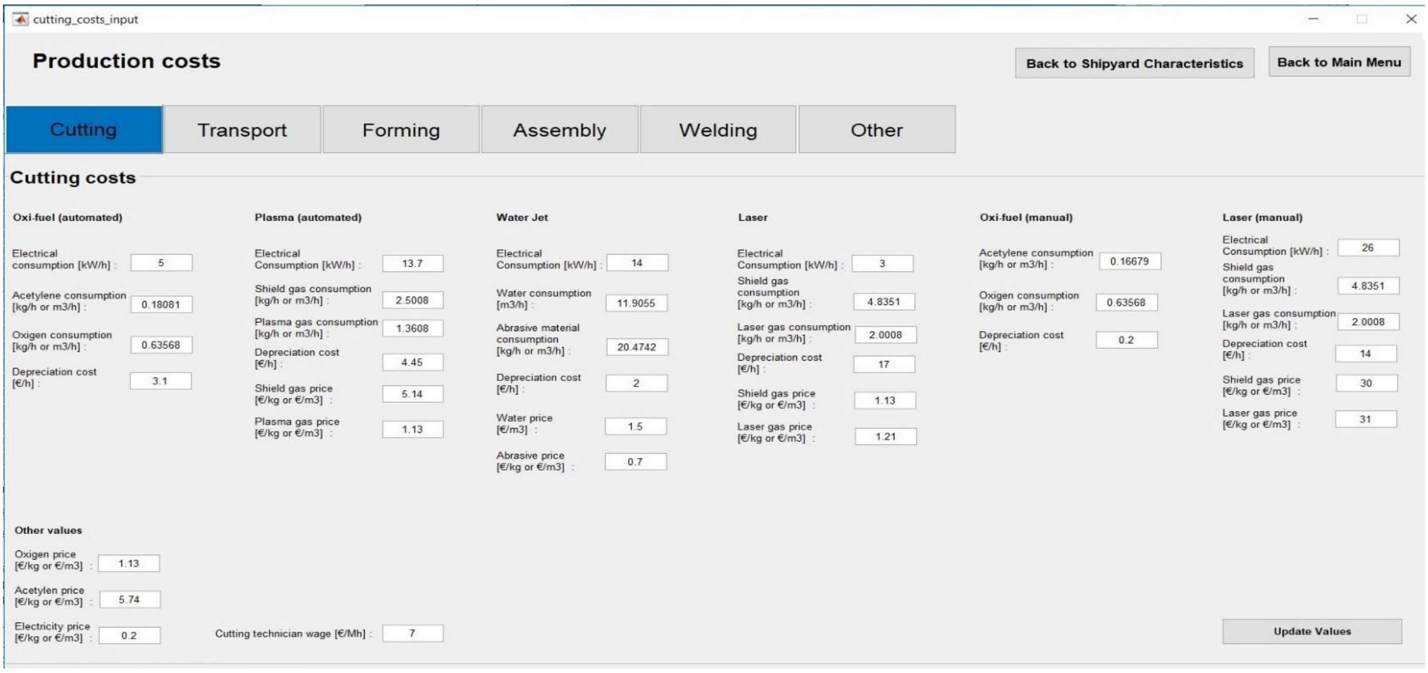


Figure 5 – Cutting technologies costs graphic interface

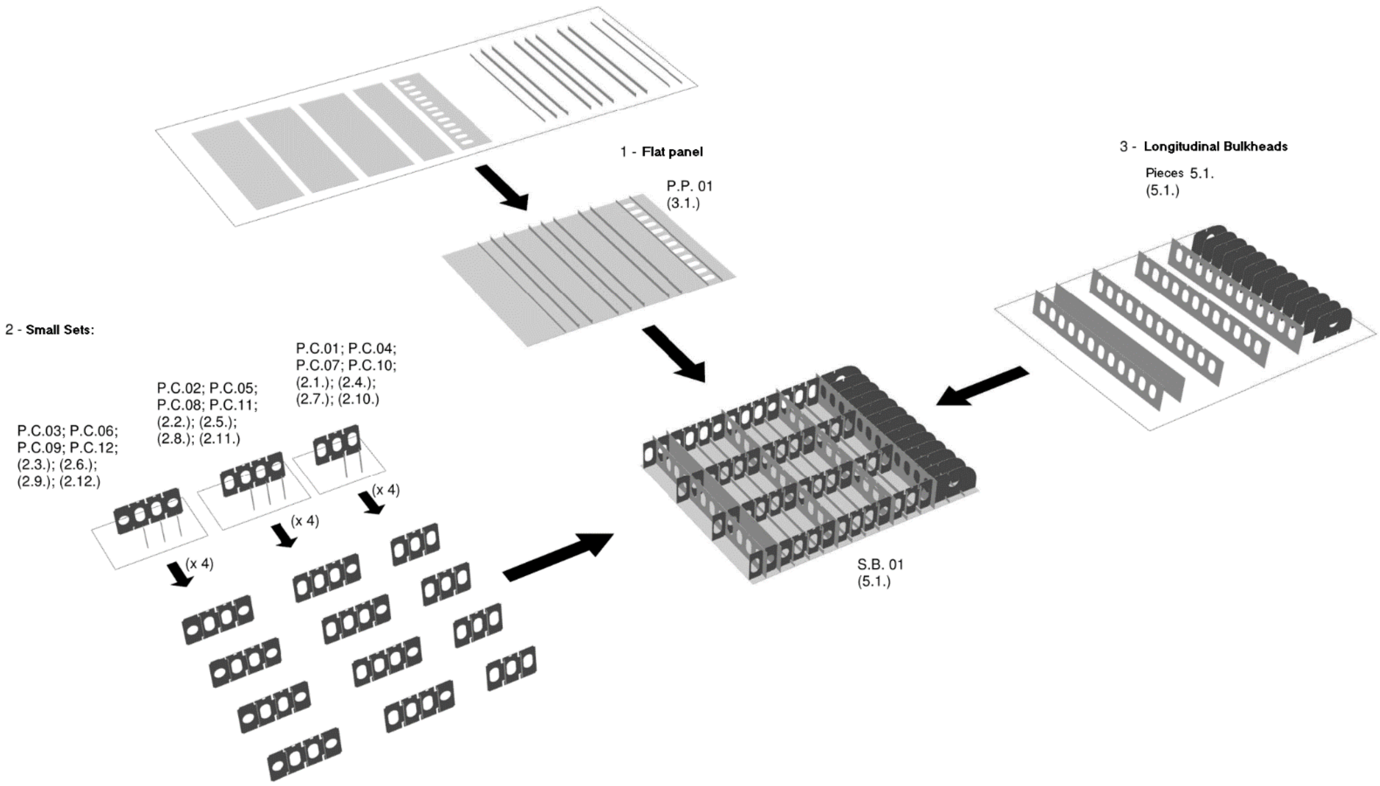
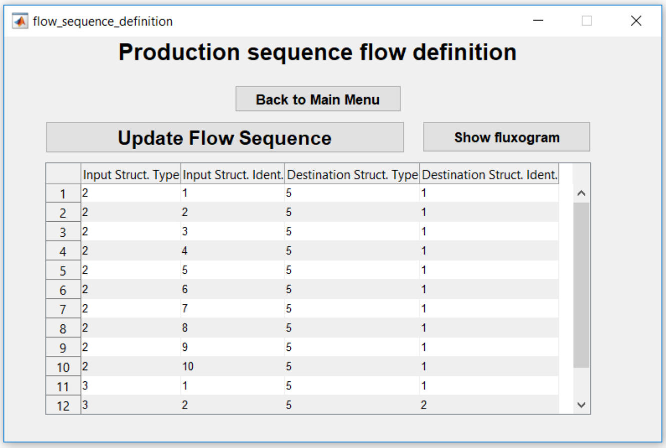


Figure 6 – Block construction sequence

The flow production sequence definition is defined through a graphic interface, as shown in Figure 7.

In the flow sequence definition, as shown above, the program presents, in the two columns of the left, a certain structure A, and, in the two columns of the right, the destination structure to which the structure A will be joined.

After defining the block and shipyard characteristics, as displayed in the present paper chapter, the needed data is completed and the computations of the cost and time analysis can be initiated.



	Input Struct. Type	Input Struct. Ident.	Destination Struct. Type	Destination Struct. Ident.
1	2	1	5	1
2	2	2	5	1
3	2	3	5	1
4	2	4	5	1
5	2	5	5	1
6	2	6	5	1
7	2	7	5	1
8	2	8	5	1
9	2	9	5	1
10	2	10	5	1
11	3	1	5	1
12	3	2	5	2

Figure 7 – Construction sequence graphic interface

2.2 *Model algorithm computations*

Considering the specifications set by the user presented in the previous chapter, the developed model computes the cost and times analysis of each one of the main stages of the steel block construction. The sequence in which the algorithm run can be illustrated in the flow shown in Figure 8:

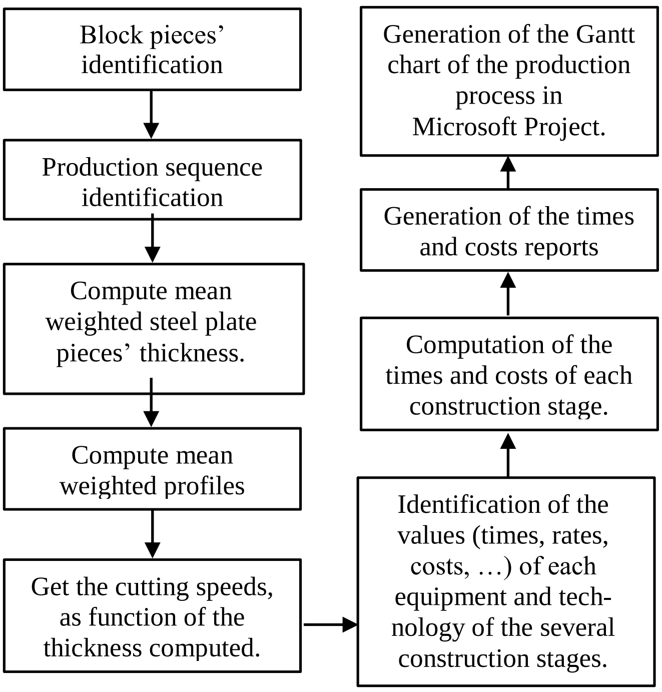


Figure 8 – Algorithm flow chart

Although it is not feasible to present in this paper all the formulas used for the computations of the several block construction stages, attending that each main construction stage got his own sequence of activities, treated each one individually, is useful for a better comprehension to exemplify with one of the several activities of one given stage, for example, the automatic cutting activity of the profile cutting stage.

After the work distribution of the profiles by each active profile cutting equipment is computed so that the stage is performed in the minimum possible time, the following set of activities are considered and analyzed:

- Location of the profile to cut;
- Transport and positioning of the profile before cut;
- Cut preparation;
- Automatic marking;
- Automatic cutting;
- Manual Cutting
- Dimensional control;
- Manual marking;
- Transport of the profile after cut.

The present example deals with the automatic cutting stage. The time need for this stage is computed simply applying the cutting speed, AC_{speed} [m/min], which was previous calculated through consideration of the cutting technology and the mean weighted thickness of the profiles, on the total profile's cutting length, $P_{cutting\ length}$ [m]:

$$AC_{time}\ [\text{min}] = \frac{P_{cutting\ length}\ [\text{m}]}{AC_{speed}\ [\text{m/min}]} \qquad (1)$$

The cost computation of the automatic cutting activity in the profiles cutting construction stage if obtained considering the following sum of items:

$$AC_{cost}\ [€] = \left(\sum_{1}^{n} CC_n\right) + DC + LC + EC \qquad (2)$$

The CC stands for the costs of the consumables, according with the type of cutting technology defined, and is computed in the following way:

$$CC_n[€] = CR_n[\text{un/h}] \times \frac{AC_{time}[\text{min}]}{60} \times CR_n[€/\text{un}] \qquad (3)$$

where:

CR_n – Consumable n flow rate [un/h];

CR_n – Consumable n specific price [€/un].

The unit [un] can stand usually for [m^3] or [l], according with the type of consumable.

The DC value of formula (2) stands for the depreciation cost of the automatic cutting equipment and is easily computed through:

$$CD[€] = ACE_{dep}[€/\text{h}] \times \frac{AC_{time}[\text{min}]}{60} \qquad (4)$$

where

ACE_{dep} – Automatic cutting equipment depreciation rate cost [€/h].

The LC value of the formula (2) stands for the labor costs and is obtained by applying:

$$LC[€] = NW \times WW[€/h] \times \frac{AC_{time}[\text{min}]}{60} \quad (5)$$

where

NW – Number of workers needed in this cutting activity phase;

WW – Worker wage [€/h].

The last item of the formula (2) concerns the electricity cost and is computed through the following formula:

$$EC[€] = PC[\text{W}] \times \frac{AC_{time}[\text{min}]}{60} \times PP[€/\text{W.h}] \quad (6)$$

where

PC – Power of the equipment [W], which can be specified also with the aim of a power efficiency value, $P_{eff}[\%]$;

PP – Power specific price $[€/\text{W.h}]$.

Is important to stress that all the above values are defined by the user either in the block pieces' definitions stage or in the shipyard characteristics set stage.

2.3 *Model validation*

The validation process of the developed model was conducted in two distinct fronts: The first concerning the cost values computed and the second concerning the time values.

For both validation processes were used two blocks, as shown in the figures 9 and 10:

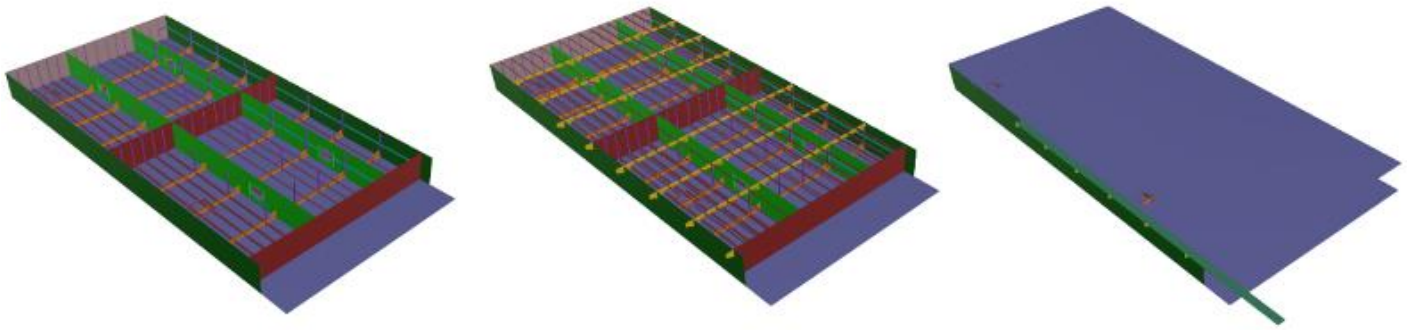


Figure 9 – Block A – pontoon block

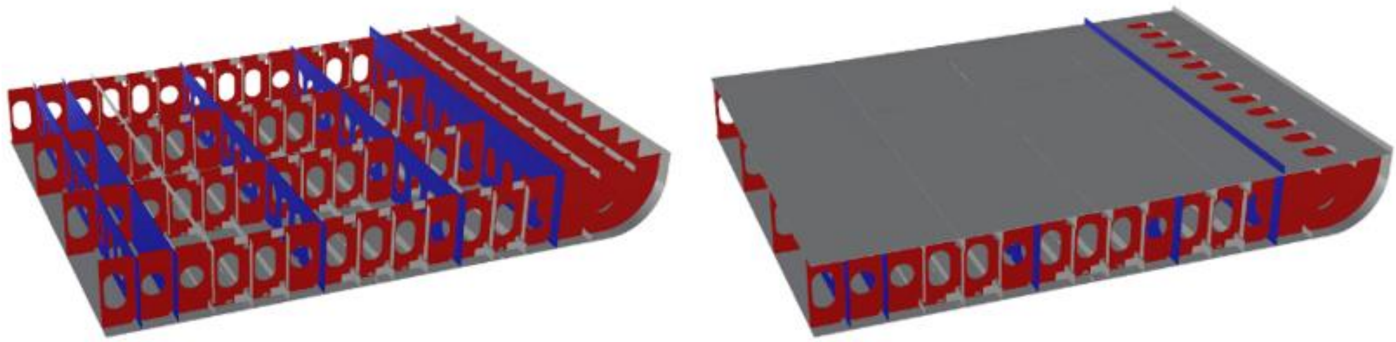


Figure 10 – Block B – double bottom block

The Block A, shown in Figure 9, belongs to a pontoon with a length of 20.78 m, breadth of 9.86 m and depth of 1.42 m, with 41 ton. The Block B, illustrated in Figure 10, is a mid-ship double bottom block of a chemical tanker, with a length of 10 m, breadth of 13 m and depth of 1.5 m, with 47 ton.

The construction sequence of Block A was performed through the assembling of 8 small structures and 2 flat panels. The combination of one sub-block and the second flat panel finish the block construction sequence. The Block A is made up of 277 steel plate pieces and 192 steel profiles. There is a total of 959 meters of steel cutting work. The steel plate pieces present a range of thickness 8 mm to 6 mm.

The construction sequence of Block B was performing through the assembling of 12 small structures and 2 flat panels. In a similar way of the Block A, the combination of one sub-block and the second one flat panel finish the block construction sequence. The Block B is made up of 138 steel plate pieces and 19 steel profiles. There is a total of 1132 meters of steel cutting work. The steel plate pieces present a range of thickness 10 mm to 15 mm.

2.3.1 *Cost analysis validation*

The cost analysis computed values were validated through the application and comparison with the model developed by Gordo & Leal (2018) .

Both blocks A and B were run in the Leal & Gordo model, as well as a production characteristics set as similar as possible to the one characterized in the model developed in the present study when running the production process also for both blocks. The values obtained in both models are presented in Table 1.

Table 1 – Cost analysis validation values. Values in [€].

		Leal and Gordo's model	Present model
Block A	Cutting	2387	2820
	Assembly and welding	10776	9949
Block B	Cutting	5066	11549
	Forming	570	1214
	Assembly and welding	1265	3388

Although a different way of study approach, where Leal & Gordo's model specify the block through a set of values, like the ones presented in Figure 2 and the developed model of the present paper requires a deeper specification of the block, it is acceptable to compare the results obtained.

Although some disparity on the values of the Block B, which can be explained by the lower structural complexity it would be expected for a double bottom block, the values presented in the Table 1 allow to validate the cost analysis values of the developed model.

2.3.2 *Time analysis validation*

To conduct the validation process of the time values computed by the developed model, was used real case data given by a construction shipyard in Portugal, WestSea S.A., hereby called WS, of four blocks (*i*, *j*, *l*, *k*) of a ship construction project.

The four blocks manufactured in the WestSea Shipyard (Block *i*, *j*, *k* and *l)* are blocks of military ships, hence it was not feasible for the Shipyard to give more detailed information rather than the total weight of the block's steel plate pieces and profiles, and the main block construction stages times.

Several block construction stages were studied separately, and the ratios [ton/day] were computed and compared with the obtained applying Blocks A and B in the developed model, as shown in Tables 2 to 6.

The validation process through the comparing method of the ratio values is done only with situations where there is a similar block characteristic, hence not all the blocks appear in all tables. Is also important to stress that the shipyard characteristics defined in the developed program were set to be as similar as possible to the ones of the WS shipyard during the construction process of the four blocks. For example, regarding the welding technologies, the butt welds performed in the plate blanket construction stage of the panel line are performed through one side automated submerged arc welding, and all the other welding works are performed through manual flux cored arc welding.

The time ratios obtained allow to validate the algorithms of the time analysis conducted by the developed model. Hence, validated the time and cost analysis, the model is validated.

Table 2 – Profiles cutting time validation values

Block	$\frac{\boldsymbol{Profiles\ weigth}[\boldsymbol{ton}]}{\boldsymbol{Cutting\ time}\ [\boldsymbol{days}]}$
Block *l* (WS)	0.62
Block *k* (WS)	0.64
Block A (model)	0.58
Block B (model)	3.89

Table 3 – Steel plate cutting time validation values

Block	$\frac{\boldsymbol{Steel\ plate\ pieces\ weigth}[\boldsymbol{ton}]}{\boldsymbol{Cutting\ time}\ [\boldsymbol{days}]}$
Block *i* (WS)	8.46
Block *j* (WS)	2.38
Block *k* (WS)	3.05
Block *l* (WS)	6.67
Block A (model)	4.31
Block B (model)	8.30

Table 4 – Plate forming time validation values

Block	$\frac{\boldsymbol{Block\ weigth}[\boldsymbol{ton}]}{\boldsymbol{Plate\ forming\ time}\ [\boldsymbol{days}]}$
Block *i* (WS)	6.4
Block *j* (WS)	6.4
Block B (model)	11.9

Table 5 – Flat panels construction time validation values

Block	$\frac{\boldsymbol{Block\ weigth}[\boldsymbol{ton}]}{\boldsymbol{Flat\ panels\ time}\ [\boldsymbol{days}]}$
Block *i* (WS)	1.75
Block *j* (WS)	2.35
Block *k* (WS)	2.97
Block A (model)	2.27
Block B (model)	7.97

Table 6 – Global block construction time validation values

Block	$\frac{\boldsymbol{Block\ weigth}[\boldsymbol{ton}]}{\boldsymbol{Block\ construction\ time}\ [\boldsymbol{days}]}$
Block *i* (WS)	0.28
Block *j* (WS)	0.44
Block *k* (WS)	0.61
Block *l* (WS)	0.16
Block A (model)	0.41
Block B (model)	0.67

2.4 *Alternative cutting technologies implementation study*

Validated the developed program is possible to undergo on a simple simulation of alternative production processes implementations. The chosen process to study on the simulation hereby presented relates to the study of implementation of alternative automatic cutting technologies. The four situations studied were:

• Situation 1 – All the cutting processes are performed through oxy-fuel cutting;

• Situation 2 – The panel line cutting stage and profiles cutting are execute with oxy-fuel, and the steel plates cutting process, to generate pieces, is performed by plasma cutting. This is actually the most similar situation when compared to the actual WesSea Shipyards S.A. production process.

• Situation 3 – All the steel cutting processes are performed through laser technology;

• Situation 4 – All the steel cutting processes are performed through abrasive water jet technology.

The time and cost values obtained by running the developed program are presented in Table 7.

Table 7 – Alternative cutting technologies scenarios

		Cutting processes		Assembly and welding processes	
Block	Situation	Time [days]	Cost [€]	Time [days]	Cost [€]
A	1	24.5	3017	109	9310
	2	21.0	2656	108	9079
	3	19.9	4469	107	8964
	4	29.0	8371	107	8906
B	1	11.4	1836	81	5414
	2	7.3	1428	81	5268
	3	7.1	1965	81	5181
	4	16.9	6917	78	5142

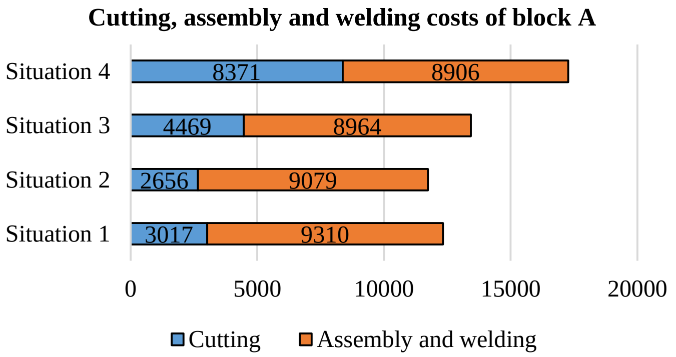


Figure 11 - Cutting costs, in [€], of the implementation of different cutting technologies in block A.

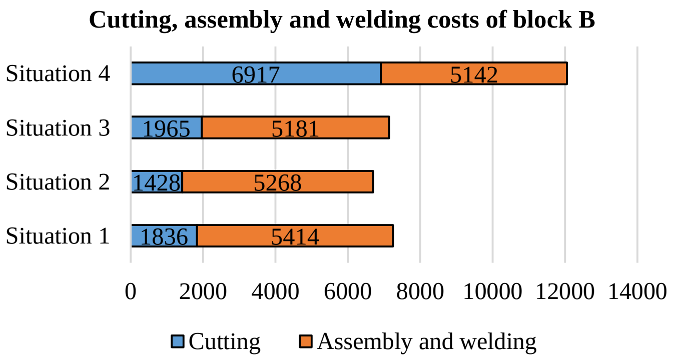


Figure 12 - Cutting costs, in [€], of the implementation of different cutting technologies in block B.

It is important to state that the calculations were conducted in a way that the differences present in the time and cost values of the various assembly and welding phases, are only justified due to the decrease of the gridding stage, resulting from the increase of cutting quality that each cutting technology allows. The analysis of the results allows to comprehend that although some decrease in the assembly and welding cost values is obtained, mainly due to cost savings by the reduction of the man-hours needed in the gridding process, the global saving is not so large as one would expect, reaching, at most 5%. This cost saving due to the reduction of work in the gridding phase do not justify per himself the increase of the cost of the cutting technologies with better cutting quality. However, is important to stress that a better cutting quality also allows important improvements in the dimensional control, decreasing possible re-works or corrections in the assembly and welding stages, although those savings are hard to estimate and, by that reason, were not consider in the developed software tool.

If one considers only the analysis on the cutting costs, the values obtained are in line with the actual shipbuilding industry, where the plasma cutting is the most attractive technology. The cutting speed of the plasma saves precious man-hours, hence balancing its higher operational costs when compared to the oxy-fuel technology and even obtaining cost savings.

As expected, the high operational costs of the laser and the low cutting speed of the waterjet cutting do not allow yet to implement economically that technologies on the ship production process at large-scale.

Although assembling and welding values are here shown together, it is possible and interesting to exemplify its time ratio, i.e., the time ratio of the assembling related works *vs* the time ratio of the welding related works. Illustrated those ratios to the Block A by applying the developed model, with similar shipyard characteristics to the WestSea Shipyard's, one has the results presented on Table 8.

Table 8 – Assembling and welding related works ratios, of Block A, for oxy-fuel cutting and water Jet cutting situations

	Oxy-fuel cutting		Water Jet Cutting	
	Assembling related works	Welding related works	Assembling related works	Welding related works
[min]	21202	18539	19346	18539
[%]	53.4	46.6	51.0	49.0

As expected, the ratio gap between the assembling related works and the welding related works increases with a higher cutting quality.

3 CONCLUSIONS

The main goal of the developed model was to prove the reliability of the implementation of an alternative approach in the block construction process study. Through a validation process was considered that such approach, implemented in the developed program, is reliable. Further studies are needed to prove higher quality level of the values computed considering the approach here chose when compared to the more classical and less detailed approach, like the ones illustrated in Figure 2.

To achieve more reliable results, further work is needed to be conducted in the developed software, mainly in the assembling and welding activities. The consideration of the weld dimensions according with the base metal thickness, as well as a deeper characterization of the consumable rates of the welding processes are some examples of future works to accomplish and implement in a better way in the developed model.

In addition to the goal of proving the reliability of this type of block production analysis, the model aims also to serve as a tool to understand the consequences of the implementation of alternative and more recent process technologies. Although the cutting technologies, even the newer, are quite well recorded in existing studies, the more recent welding technologies have not yet well defined published parameters of consumes rates. Such data is fundamental to perform a reliable analysis, and that was the reason why the authors only simulated alternative scenarios with different cutting technologies.

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