Proceedings of the 2017 Winter Simulation Conference
W. K. V. Chan, A. D'Ambrogio, G. Zacharewicz, N. Mustafee, G. Wainer, and E. Page, eds.

APPLICATION OF A MULTI-LEVEL SIMULATION MODEL FOR AGGREGATE AND DETAILED PLANNING IN SHIPBUILDING

Mar Cebral-Fernández
Marcos Rouco-Couzo
Marta Quiroga Pazos

Area of Modeling and Simulation
UMI Navantia - UDC
Campus Industrial
Ferrol, 15403, SPAIN

Diego Crespo-Pereira
Alejandro García del Valle

Polytechnic School
Universidade da Coruña
Campus Industrial
Ferrol, 15403, SPAIN

Rafael Morgade Abeal

Department of Production Management
Navantia Ferrol
C/ Taxonera, S/N
Ferrol, 15403, SPAIN

ABSTRACT

Shipbuilding is one of the most complex manufacturing processes due to the high number and diversity of elements involved throughout the production process. Particularly challenging is the production of singular vessels, such as frigates, where effective planning becomes crucial for delivering the vessel on schedule due to the uniqueness of the product and the lack of historical data of previous equivalent constructions associated to this singularity. In this study, an ongoing simulation-based model that minimizes the uncertainties of the shipbuilding process is presented. Using the Discrete Event Simulation software ExtendSim, three real case studies are presented for the model validation. The objective is to obtain a multi-level model that can be used not only at early stages of the project, when detailed specifications are yet unavailable, but also at later stages, when design is well advanced and extensive data become accessible.

1 INTRODUCTION

The shipbuilding industry is characterised by being an industry that provides one-of-a-kind products, rarely produced in series, with high value added units and lengthy construction periods. The world shipbuilding market is also defined by intense competition. Prices have been declining, partly because of substantial overcapacity. The industry faces fierce international competition, forcing the shipbuilders to increase their performance with a focus on being able to adapt their process under different technical and managerial scenarios (Lamb et al. 2006). This is particularly difficult in the case of frigates construction, where the serial production is practically nonexistent. Due to this unique nature, the supply, planning and scheduling phases become extremely complex since no reliable historical data are available for the successful development of the early phases prior to the construction of the ship (Duclos, Vokurka, and Lummus 2003).

Given the peculiarities of this industry, adequate planning and scheduling become paramount for the success of the projects. On the one hand, the coordination of the different workshops involved in the ship construction process has a significant impact on performance and quality. In fact, this is a key factor for the competitiveness of European shipbuilders. On the other hand, milestones agreed with the client at the signing of the contract (keel, launch and delivery) must be accomplished. These milestones are used by the shipyard planners as a basis for the planning of the erection (assembly) of blocks at the slipway (Meijer, Pruyn, and Klooster 2009). Block erection is usually the bottleneck in most European shipyards (Krause et al. 2004) and point out the production capacity of the workshop. Moreover, the blocks manufacturing sequence must be precisely planned to ensure their proper arrival at the slipway, considering not only the assembly sequence restrictions but also the manufacturing times of each block as well as resources availability throughout the entire process.

Due to the nature of the shipbuilding process, simulation has not been widely used within the industry (Shin, Kwon, and Ryu 2008). The large number of operations required to produce the blocks of a ship, the necessity to synchronize multiple workflows and numerous resources make the management of such production system very challenging. Due to this idiosyncrasy, simulation represents an extremely powerful tool for the decision making process that proves to be useful to test and evaluate different scenarios to efficiently plan potential future investments and resources allocation, reducing drastically the risks of making wrong decisions. The NRC (1998) identified simulation as one of the most important breakthrough technologies that would accelerate progress in addressing the grand challenges in manufacturing in the 2020, anticipating that simulation would allow making decisions based on alternative scenarios.

In recent years, different types of simulation modeling approaches have been investigated in various attempts to address the peculiarities of shipbuilding. Several researches have contributed to the development of simulation in the civil engineering industry (for instance, see Burnett et al. 2008). In shipbuilding, Kiran et al. (2001) employed simulation to evaluate production schedules, resource utilization, material and work flow and capacity.

The most remarkable studies on the spatial scheduling problem in shipyards was done in the context of the DAS project (Lee et al. 1995). Cho et al. (2001) and Park et al. (2002) presented a series of algorithms to optimize workspace utilization for the block painting process. Years later, Zheng et al. 2017 developed a greedy algorithm with the objective of minimizing the makespan by focusing on spatial scheduling strategies. Zhuo, Huat, and Wee (2012) developed a hybrid planning method that used simulation to perform look-ahead scheduling. Other works have focused on locally planning specific portions of the section assembly process (Seo et al. 2007). Rose and Coenen (2016) have been working successfully with genetic algorithms to automatically generate section building schedules. Some authors have recently developed hybrid models with the aim of improving the productivity of shipyard workshops as Caprace et al. (2011) and Bair et al. (2013).

In the last decade, new initiatives to accelerate the development of simulation in the shipbuilding industry have arose, such as the group SimCoMar (Simulation Cooperation in Maritime Industries) and SIMoFIT (Simulation of Outfitting in Shipbuilding and Civil Engineering) (Steinhauer 2011). Also, many shipyards have started to work with model simulation as in Flensburger Schiffbau-Gesellschaft, Meyer and Aker Ostsee in Germany and many Asian shipyards. Nowadays in Spain, unlike other fields such as the aerospace and the automotive industries where it is strongly consolidated, the use of simulation in the shipbuilding industry is yet to be explored.

2 PROCESS DESCRIPTION

The shipbuilding industry stands out from other industries since, as opposed to others, such as the automotive industry, it is a make-to-order manufacturing, being every vessel designed and constructed based on the owner's requirements. Therefore, it is important to understand that the shipbuilding industry comprises of manufacturing processes significantly different from those of other industries. A schematic of the processes undertaken at the shipbuilding under study are shown in Figure 1:

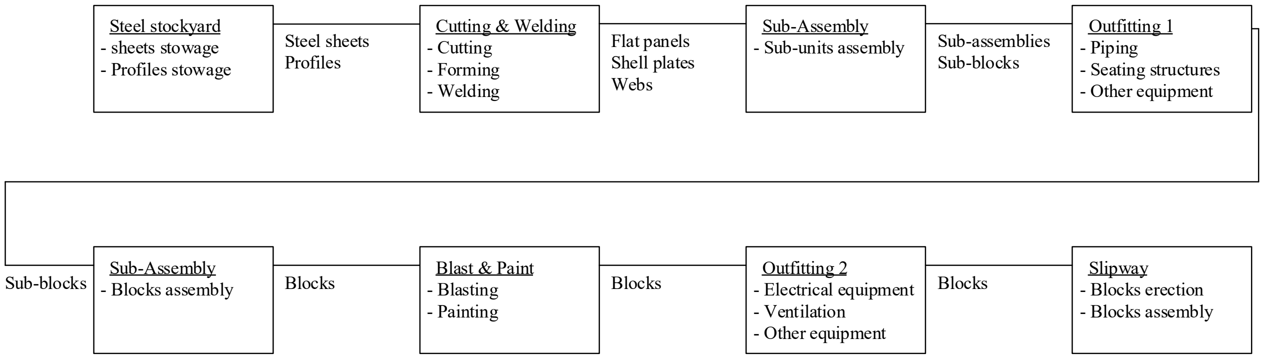

Figure 1: Shipyard operations flow.

The shipbuilding process can be broken down into several parts: steel stockyard, Cutting & Welding workshop, Sub-Assembly workshop, Outfitting 1 workshop, Blasting & Painting cabins, Outfitting 2 workshop and Slipway.

- Steel stockyard: On arrival at the site, steel sheets and structural profiles are temporarily stored in the steel stockyard.
- Cutting & Welding workshop: This workshop receives two different inputs: steel sheets and structural profiles, both arriving at the workshop from the steel stockyard. Steel sheets are transformed into two different elements: plates and webs, being the latter a type of stiffening element that will be later on assembled to the panel. Plates are themselves used for two different operations: flat panels and curved shell plates, being the latter those who form the outer structure of the hull. Prior to their arrival, plates undergo nesting, a process undertaken by the Design department, in which plates are divided into the shapes they should be cut out, making sure minimum scrap metal is produced from each plate. Plates are then cut into required shapes and sizes, as per the nesting plan, in order to be developed to the required shapes. Structural profiles are also cut at this workshop. Another operation undertaken at this workshop is forming. Those plates that will be developed as shell plates and webs are bent to the desired curvature. Once the plates and the webs are prepared and given the required shape, they are welded together on the panel-line. This first sub-assembly will be composed of a plate and its longitudinal stiffeners and webs.
- Sub-Assembly workshop: This workshop is divided into 16 separate bays, where assembly of sub-units is carried out. The cut and formed plates and their processed components are assembled into subsequent sub-units. Adjacent sub-assemblies are welded together at this workshop to form three dimensional structures. Frigates are divided into blocks, being them of full width of the ship, in the vast majority of frigates produced by the shipyard under study. Blocks, at the same time, are divided into smaller sub-assemblies called sub-blocks, and sub-blocks are subsequently formed by smaller sub-assemblies called panels.
- Outfitting 1 workshop: This workshop is divided into 6 bays for outfit of equipment. In parallel to the previous processes, outfit equipment is fabricated at the dedicated auxiliary workshops, to ensure its availability when required. At this first outfitting stage, piping, brackets and other equipment are installed on the sub-blocks. Adjacent sub-blocks are sent back to the Sub-Assembly workshop and welded together to erect a block.
- Blasting & Painting cabins: Once the block is assembled, blasting and painting are performed at the Blasting & Painting cabins.

- Outfitting 2 workshop: The workshop includes 7 separate bays. At this stage, outfitting of electrical equipment, ventilation ducts and other equipment is undertaken on the blocks.
- Slipway: Once all the blocks are assembled, they are ready to be sent to the building slipway, where they are erected, as per the assembly sequence and after each erection, welding is carried out on block joints. Once the frigate is built, it is launched, and sea trials are performed prior to final delivery to the client.

3 MODEL DEVELOPMENT

The innovative nature of the simulation model lies in the fact that it can be used at both an aggregate and a detailed level.

At an aggregate level, it proves to be particularly useful at the initial stages of the project, such as the tender phase, when only basic engineering has been developed. Starting from historical data of previous equivalent constructions undertaken at the shipyard, the model is used to develop an initial aggregate plan that ensures compliance with the milestones imposed by the client.

At a more specific level, when detailed engineering has been developed and precise realistic product data become available, the model proves to be effective to examine specific aspects of the construction process and to analyze the workshops in much greater detail. Being appropriate, among other things, to detect inefficiencies at particular workshops to afterwards act on them, to test the impact that different modifications in a workshop would have locally, as well as on the overall process or to develop a detailed plan that delivers the product on time to the next workshop ensuring a more balanced load and utilization of internal resources. This requires the definition of the input attributes and variables that will characterize both the processes undertaken at the shipyard and each of the components that will conform the ship.

3.1 Model data

The entire process has been modeled and simulated using the DES software ExtendSim. The high-resolution level that such a complex production process requires, makes ExtendSim an excellent solution that entirely complies with the model requirements. A critical aspect that has been taken into consideration when selecting this software has been the ease of integration with tools extensively used at the shipyard, such as Microsoft Excel and SAP, so as to facilitate the data entry process and the simulation results comprehension for the shipyard planners and the shop floor foremen. Strong efforts in data collection and analysis have been made in the interest of achieving the most accurate parametrization of the ship components.

3.2 Blocks and Sub-blocks

The simulated frigate is composed of 50 sub-blocks which are assembled in turn into 25 blocks. In order to represent the complete workload of the frigate, the sub-blocks have been categorized based on their structural characteristics, resulting in 5 typologies, for each of which, a sub-block has been selected for being the most representative of the typology. Each of these selected sub-blocks has been thoroughly analyzed. The main attributes that characterized these 5 sub-block are listed in Table 1.

Table 1: Main sub-blocks attributes.

Typology	No. Web frames	No. Beams
Weight	No. Longitudinal girders	No. Spare parts (webs)
No. Straight panels	No. Transverse girders	No. Profiles (webs)
No. Shell panels	No. Double bottom girders	No. Spare parts (panels)
No. Longitudinal profiles	No. Bulkheads	No. Profiles (panels)

Once these sub-blocks are entirely defined, the attributes of the remaining sub-blocks are automatically generated by a VBA Macro, distributing the elements proportionally based on their weights. Other more specific attributes, such as the number of pipes, sub-blocks dimensions, etcetera, are useful to define the rest of the sub-blocks individually.

Then, the input sequence plan can be added. An Excel file contains information of the cutting schedule for each sub-block, that is, the input sequence of the steel sheets and the profiles into the first workshop. The more reliable these data are, the more accurate the results will be at this first planning stage. In this regard, an important aspect to bear in mind is the assembly sequence constraint at the slipway. This sequence, that is predefined by the ship construction strategy at an initial stage of the project, acts as a fixed variable in the model. There is only one possible positioning sequence for the blocks due to structural and engineering restrictions. Therefore, when a block reaches the last stage (location on the slipway), a delay will take place if the previous block is not located yet.

3.3 Disaggregation process

Once the main sub-blocks attributes are defined and the blocks are loaded into the model, a splitting process takes place. Sub-blocks are therefore automatically exploded into their constituent components, generating a detailed breakdown of every element that composes the vessel. During this disaggregation process, more properties are added to the items. The model resolution allows to simulate from the smallest parts (steel sheets or profiles) to complete enormous blocks. At the aggregate-level stage, the components breakdown belongs to a previous equivalent vessel and will be replaced by actual data of the current construction once they are available.

An exhaustive analysis of the ship components as well as of the construction process was conducted for the purpose of defining the attributes and the ratios employed along the various phases of the construction process. The main data analysis is described in Table 2.

Table 2: Main data analyzed.

Sheets cutting lengths
Welding lengths
Sheets thicknesses
Transport lot sizes
Profiles dimensions
Sheets dimensions

This part of the analysis have entailed important difficulties due to the number and diversity of the ship components. As an example, in the case of the webs welding lengths, more than 1,200 engineering plans have been analyzed to fit the adequate statistical distribution.

3.4 Simulation process

In the first workshops, during the simulation, the components of each block are processed and assembled as per the bill of materials. Then, the blocks/sub-blocks go through the successive workshops, to finally reach the slipway. These blocks are created as the pieces are grouped into their pertinent block and they go through different operations in the workshops.

All the processes carried out in the workshops are characterized and represented. A laborious task has been conducted to identify the information that best represents the operations undertaken at the workshops. A small sample of the operations ratios is listed in Table 3, which represents a very small proportion of the total number of ratios used in the model. Specifically, it refers to the first cutting station of the Cutting and Welding workshop.

Table 3: Cutting station ratios.

Capacity (Number of steel sheets)
Loading (s)
Waste removal (s)
Edge treatment (m/min)
Cutting process (m/min)
Unloading (s)

With the purpose of facilitating the data entry process to the shipyard planners, an Excel control panel has been developed. This, along with the parametric behavior of the model, allows to easily change ratios and durations in the model. This Excel file is connected with the model via an Excel VBA Macro and contains the most representative data of the operations carried out at the workshops.

By means of an Excel VBA Macro, the model allows to export the total amount of time that each sub-block/block has stayed in the different workshops, enabling to distinguish between effective production time and that attributed to delays. The results can be exported to a table and, simultaneously, a Gantt chart is automatically generated. Figure 2 shows the sequence followed by the simulation model.

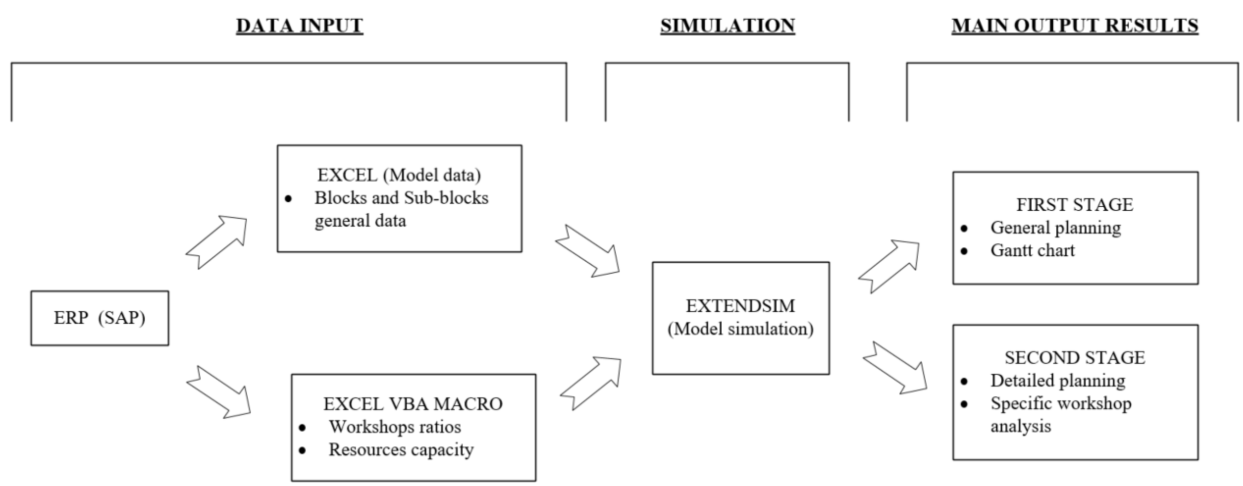

Figure 2: Simulation process flow.

4 EXPERIMENTATION AND RESULTS

Examples of different experimentations that have been performed that confirm the multi-level nature of the model are presented below. The first experiment addresses the problem of aggregate planning at early stages of the project, whereas the last two focus on the detailed analysis of a particular workshop.

4.1 Analysis of an improved production schedule

As stated before, the blocks assembly sequence is a fixed variable that is predefined by the Construction Strategy. It is therefore necessary to plan and stablish the proper timing for starting to produce the components of the blocks, ensuring their arrival at the slipway in time to be erected as per the assembly sequence. While it is possible to synchronize these input/output sequences, it is cumbersome, partly due to the big differences between blocks/sub-blocks in dimensions, shapes, structural conditions, etcetera and partly because the process is not linear, meaning several blocks/sub-blocks are built at the workshops simultaneously. This peculiarity implies a hard planning work since the construction of a ship is an enormous project that requires the synchronization of many resources during the project lifetime.

The model easily allows to evaluate not only different sub-blocks input sequences but also the right day to start the production of each sub-block components.

In this experiment, the manufacturing planning sequence at early stages of the project has been analyzed, when detailed technical data are yet unavailable. A proper solution is expected to be reached after the comparison between two different planning sequences: real planning of a similar frigate and an improved one.

In order to find a good approach that satisfies the temporal construction requirements, that is, the improved one, several considerations have been made. Since the Blasting & Painting cabins have been proved to be the most restrictive resource in the shipyard, this first planning sequence has been made taking into account the optimization of this limiting resource. A preliminary simulation has been conducted in order to estimate the stay time of each block in every stage of the construction process. These durations, without considering delays, represent the blocks and sub-blocks net manufacturing time.

Since the net manufacturing time and the arrival sequence at the slipway are known, a first sequence has been calculated. Besides, a second sequence was reached taking into consideration a proper arrival of the blocks to the Blasting & Painting cabins. A first approximation to a valid blocks input sequence has been reached, therefore, the experiment consisted in the simulation of this new and improved input sequence. The results were compared with the simulation of the input planning sequence of a real frigate, for that, the model was also loaded with the input sequence followed previously in the shipyard for the construction of an equivalent frigate

After analyzing both results, the improved input sequence showed a 30% makespan reduction regarding the real manufacturing of the equivalent ship. It must be noted that both simulations have been carried out under the same conditions and assumptions, without considering certain restrictions such as suppliers delays, engineering restrictions, etcetera.

The model generates results focusing on the manufacturing process, therefore it is useful for the company to evaluate the benefits related to the reduction of lead time. When the simulation is finished, a Gantt chart is automatically generated (Figure 3), showing the sub-blocks stay times along the various stages of the construction process: from the Cutting & Welding workshop to the Slipway.

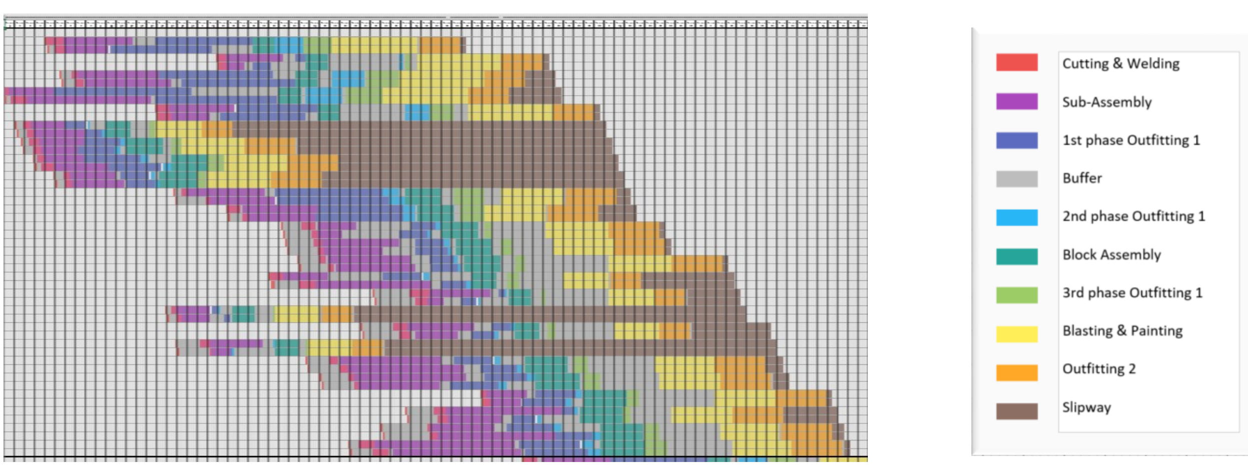

Figure 3: Process blocks Gantt chart. Improved input sequence.

The improved input sequence have shown a considerable makespan reduction as well as a better resource utilization. As a consequence, delays have been drastically reduced by balancing the workload along the whole process. Figure 4 and Figure 5 show the different utilization rates at the Sub-Assembly workshop obtained from the aforementioned simulations. Figure 4 shows a significantly more balanced usage of the subassembly bays than that shown in Figure 5.

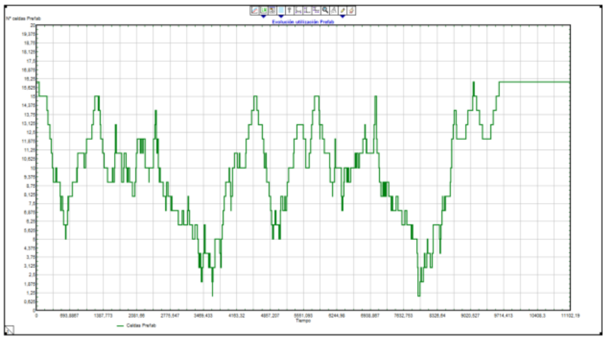

Figure 4: Available bays, subassembly workshop. Improved ship sequence.

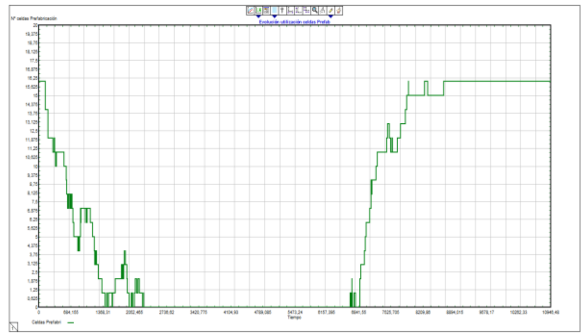

Figure 5: Available bays, subassembly workshop. Real ship sequence.

Additionally, the amount of blocks in buffers along the shipyard has been considerably reduced. In Figure 6 it can be observed a lower number of blocks in the shipyard waiting for painting process compared with the amount of blocks resulting from the real simulated sequence (Figure 7). Figure 6 shows a maximum of 6 blocks waiting to be painted while in Figure 7 the amount is double, besides the waiting times are shorten in the improved sequence (Figure 6) regarding the real one (Figure 7). These kinds of results are critically important in terms of costs and the use of resources in the shipyard industry.

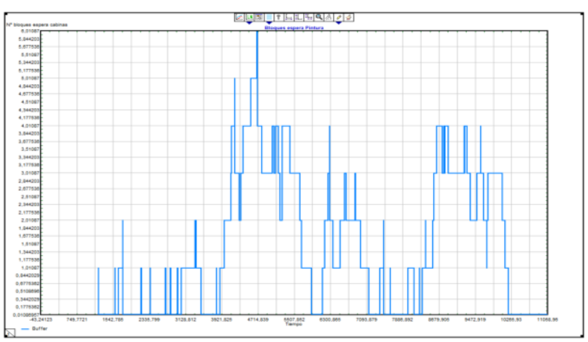

Figure 6: Buffer of blocks waiting for painting process. Improved ship sequence.

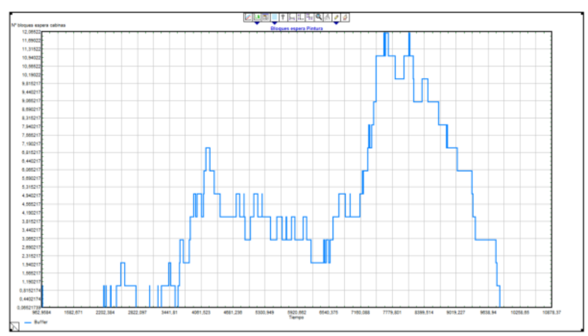

Figure 7: Buffer of blocks waiting for painting process. Real ship sequence.

4.2 Detailed Analysis of the Cutting & Welding workshop

The Cutting & Welding workshop is, as explained previously, the first of the shipbuilding process, where the basic structural elements of the ship are constructed. Thus, being capable of producing the components that will be required for subsequent operations in a timely manner becomes paramount for the success of the project.

The Cutting & Welding workshop receives two different products from the stockyard: structural profiles and steel sheets. Both will later undergo different processes depending on the element they will form part of: a web or a panel. Profiles suffer a blasting process before being sent to the oxi-cut station, where they are cut to the required length. Steel sheets, on the other hand, are sent to two different plasma cutting stations, that differentiate between those that will later on belong to a web and those that will be part of a plate. After being cut to the desired shapes and sizes, plates that will be used as panels will be sent to the panel line and those destined to be part of a web will go through the web line.

Plates go through a number of automated operations along the panel line. They are assembled at the One Side Welding Station (OSW), then they are rotated at the Panel Turning Unit (PTU), marked and blasted at the Marking & Blasting Gantry (MBG), to then being subsequently sent to the Stiffener Mounting & Welding Portal (SMWP), the Service and Stiffener Mounting Portal (SSMP) and the Vision Robot Welding Portal (VRWP), where firstly longitudinal stiffeners and secondly webs are welded to the panel. Webs go through an equivalently automated line, passing through the Service and Stiffener Mounting Portal (SSMP) and the Vision Robot Welding Portal (VRWP). Webs produced at the workshops are very different in shape. Being most of them unique and varying depending on the structural function they will be destined for (longitudinal girders, web frames, double bottom girders, soled floors, bulkheads, beams, etc.). Every single operation undertaken at the workshop has been incorporated to the simulation model.

The simulation model was used to conduct a series of experimentations, where a realistic workload scenario was represented, with the aim of providing a capacity design of the workshop that meets the makespan requirements at minimum cost. An initial screening process was made to assess which were the limiting resources, demonstrating that the web line was the slowest. Further analysis revealed that the welding station was the bottleneck of the web line. The results of the simulation experiment, based on 5 runs, show that the utilization rate of the cutting station was 29.0%, whereas the welding station was occupied 97.2% of the time.

After analyzing the intrinsic costs associated with acting on the various stations it was seen that increasing the capacity of the welding station at the web line would increase the overall workshop capacity, reducing the total makespan to half.

The simulation model proved to be a useful tool to analyze the impact that the resources capacity would have on the overall makespan, being capable of finding the best solution that meets the time requirements with the minimum number of resources allocated. It was also proved to be effective in identifying bottlenecks to afterwards select the most appropriate actions to alleviate them. Further details of the experiment can be found in the paper (Rouco-Couzo et al. 2016).

4.3 Analysis of the maximum capacity of the panel line

The model has been used to determine the maximum capacity of the panel line. This has been achieved by saturating the line, so it was the most occupied resource in the entire workshop. The experiment has been done under such conditions that beams and longitudinal girders, two types of webs that to date, had been incorporated to the panel at a later stage, were now assembled at the panel line.

To achieve this saturation, the totality of the elements that make up two identical frigates were generated at the beginning of the simulation, obtaining the maximum throughput of the line.

A number of combinations of mounting (SSMP) and welding stations (VRWP) were tested (the panel line is currently configured by one mounting station and two welding stations and operates on one shift). It was also analyzed the impact that an additional shift in the panel line would have on the overall capacity.

The most cost-effective combination was the one configured by two mounting and two welding stations as evidenced by Table 4 below. The model allows the planner to test various alternatives to find the best cost-effective approach. The decision on whether to add an additional shift or not will depend on the capacity required to comply with the milestones agreed with the client.

Table 4: Panel line maximum throughput comparison.

Shifts	Mounting stations	Welding stations	Max. throughput (95% CI) (panels/week)	Max. throughput (95% CI) (blocks/week)
1	1	1	2.598 ± 0.015	0.411 ± 0.002
	1	2	2.756 ± 0.014	0.436 ± 0.002
	2	2	4.646 ± 0.042	0.735 ± 0.007
	2	4	4.759 ± 0.042	0.753 ± 0.007
	2	1	3.686 ± 0.026	0.583 ± 0.004
2	1	1	5.138 ± 0.060	0.813 ± 0.010
	1	2	5.487 ± 0.044	0.868 ± 0.007
	2	2	9.340 ± 0.110	1.478 ± 0.017
	2	4	9.550 ± 0.066	1.511 ± 0.010
	2	1	7.365 ± 0.053	1.165 ± 0.008

5 CONCLUSIONS

In this study an ongoing simulation-based model that minimizes the uncertainties of the shipbuilding process is presented. Using the DES software ExtendSim, three real case studies have been analyzed. The model works at two stages which coincide with different phases of the ship construction: aggregate (initial phase) and detailed (advanced phase).

The first experiment addresses the problem of aggregate planning at early stages of the project. The model proved to be particularly useful to make planning decisions at an initial project stage, when detailed technical data are yet unavailable. Additionally, an improved blocks input sequence was tested, evidencing not only a reduction in the makespan but also a more balanced utilization of the resources throughout the entire project lifecycle. The second and third experiments focus on the detailed analysis of a particular workshop: The Cutting & Welding shop. The second experiment proved the model was effective to identify bottlenecks and to analyze the effect that acting on the resources capacity would have on the makespan, obtaining the solution that best meets the time requirements with the minimum number of resources allocated. The third experiment was used to determine the maximum capacity of the panel line and various alternatives that comply with the client milestones have been found and tested.

ACKNOWLEDGMENTS

This research has been developed under the initiative Industry 4.0, undertaken by the Area of Modeling and Simulation of the Joint Research Unit Navantia-UDC. The authors are thankful to Navantia and to the University of A Coruña for its valuable support as well as to Xunta de Galicia and Axencia Galega de Innovación (GAIN) that financed this Research Unit.

REFERENCES

Bair, F., Y. Langer, J. D. Caprace, and P. Rigo. 2013. "Modelling, Simulation and Optimization of a Shipbuilding Workshop". *Journal of Chemical Information and Modeling* 53: 1689–99.

Burnett, G. A., D. J. Medeiros, D. A. Finke, and M. T. Traband. 2008. "Automating the Development of Shipyards Manufacturing Models". In *Proceedings of the 2008 Winter Simulation Conference*, edited by S. J. Mason, R. R. Hill, L. Mönch, O. Rose, T. Jefferson, and J. W. Fowler, 1761–67. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Caprace, J. D., R. Moreira, L. F. Assiss, C. Martin, and P. Rigo. 2011. "Discrete Event Production

Simulation in Shipyard Workshops". In *Proceeding of the 21th COPINAVAL*, 20.

Cho, K. K., K. H. Chung, C. Park, J. C. Park, and H. S. Kim. 2001. "A Spatial Scheduling System for Block Painting Process in Shipbuilding". *CIRP Annals - Manufacturing Technology* 50: 339–42.

Duclos, L. K., R. J. Vokurka, and R. R. Lummus. 2003. "A Conceptual Model of Supply Chain Flexibility". *Industrial Management & Data Systems* 103 (6): 446–56.

Kiran, A. S., T. Cetinkaya, and J. Cabrera. 2001. "Hierarchical Modeling of a Shipyard Integrated with an External Scheduling Application". In *Proceedings of the 2001 Winter Simulation Conference*, edited by B. A. Peters, J. S. Smith, D. J. Medeiros, and M. W. Rohrer, 877–81. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Krause, M., F. Roland, D. Steinhauer, and M. Heinemann. 2004. "Discrete Event Simulation: An Efficient Tool to Assist Shipyard Investment and Production Planning". *Journal of Ship Production* 20: 176–82.

Lamb, T., H. Chung, M. Spicknall, J. G. Shin, J. H. Woo, and P. Koenig. 2006. "Simulation-Based Performance Improvement for Shipbuilding Processes". *Journal of Ship Production* 22 (2): 49–65.

Lee, J. K., K. J. Lee, J. S. Hong, W. Kim, E. Y. Kim, S. Y. Choi, H. D. Kim, O. R. Yang, and H. R. Choi. 1995. "DAS : Intelligent Scheduling Systems for Shipbuilding". *The AI Magazine* 16: 78–94.

Meijer, K., J. Pruyn, and J. Klooster. 2009. "Early Stage Planning Support". In *International Conference on Computer Applications in Shipbuilding 2009*, 2:1023–27.

Committee on Visionary Manufacturing Challenges NRC. 1998. *Visionary Manufacturing Challenges for 2020*. Edited by DC: National Washington and Academy Press.

Park, C., K. H. Chung, J. C. Park, K. K. Cho, T. H. Baek, and E. I. Son. 2002. "A Spatial Scheduling Application at the Block Paint Shop in Shipbuilding: The HYPOS Project". *Production Planning & Control* 13: 342–54.

Rose, C. D., and J. M. G. Coenen. 2016. "Automatic Generation of a Section Building Planning for Constructing Complex Ships in European Shipyards". *International Journal of Production Research* 54. Taylor & Francis: 6848–59.

Rouco-Couzo, M., D. Crespo-Pereira, A. Garcia-del-Valle, M. Cebral-Fernandez, and R. Rios-Prado. 2016. "Discrete Event Simulation to Improve Cutting-Welding Workshop in a Shipyard". In *Proceedings of the 28th European Modeling and Simulation Symposion (EMSS 2016)*.

Seo, Y., D. Sheen, and T. Kim. 2007. "Block Assembly Planning in Shipbuilding Using Case-Based Reasoning". *Expert Systems with Applications* 32: 245–53.

Shin, J. G., O. H. Kwon, and C. Ryu. 2008. "Heuristic and Metaheuristic Spatial Planning of Assembly Blocks with Process Schedules in an Assembly Shop Using Differential Evolution". *Production Planning & Control* 19: 605–15.

Steinhauer, D. 2011. "The Simulation Toolkit Shipbuilding (STS) –10 Years of Cooperative Development and Interbranch Applications". *Compit11*, 453–65.

Zheng, J., Z. Jiang, Q. Chen, and Q. Liu. 2017. "Spatial Scheduling Algorithm Minimising Makespan at Block Assembly Shop in Shipbuilding". *International Journal of Production Research*. 49:2351–71.

Zhuo, L., C. K. D. Huat, and K. H. Wee. 2012. "Scheduling Dynamic Block Assembly in Shipbuilding through Hybrid Simulation and Spatial Optimisation". *International Journal of Production Research* 50: 5986–6004.

AUTHOR BIOGRAPHIES

MAR CEBRAL FERNÁNDEZ is a Research Engineer of the Area of Modeling and Simulation at the UMI Navantia-UDC (University of A Coruña). She holds an M.Sc. in Industrial Engineering in the specialty of Industrial Management from University of Vigo (Spain) and is currently studying a Ph.D. in Marine and Industrial Engineering at the University of A Coruña (Spain). Her e-mail address is mar.cebralf@udc.es.

MARCOS ROUCO COUZO graduated with an M.Sc. in Industrial Engineering from University of A Coruña and is currently a Ph.D. student in the aforementioned university, under the doctoral program of Marine and Industrial Engineering. He is a Research Engineer at the M&S Area of the UMI Navantia-UDC. His email address is marcos.rouco@udc.es.

MARTA QUIROGA PAZOS works as a Research Engineer for the UMI Navantia-UDC, within the Area of M&S. She holds a B.Sc. in Industrial Design Engineering from University of A Coruña and a M.Sc. in Industrial Management Engineering with specialty in Logistics and Supply Chain from University of Vigo. She is currently a Ph.D. student in the Marine and Industrial Engineering program of the University of A Coruña. Her e-mail address is marta.quiroga.pazos@udc.es.

DIEGO CRESPO PEREIRA is Assistant Professor of the Polytechnic School at the University of A Coruña. He holds a Ph.D. in Industrial Engineering. He also works in the GII of the UDC as a Research Engineer since 2008. He is mainly involved in the development of R&D projects related to industrial and logistical processes optimization. He also has developed projects in the field of human factors affecting manufacturing processes. His email address is diego.crespo@udc.es.

ALEJANDRO GARCÍA DEL VALLE is Full Professor in the Polytechnic School at the UDC. He is Head of the Industrial Engineering Area of the GII and Head of the M&S Department of the UMI Navantia-UDC. He graduated in 1977 in Industrial Engineering by the Polytechnic University of Madrid (Spain) and holds a Ph.D. in Industrial Engineering from the University of Navarra (Spain). He has led numerous research projects about simulation and optimization of industrial, logistical and service systems. His email address is agvalle@udc.es.

RAFAEL MORGADE ABEAL is Manager of the Production Management Department of the shipbuilding company Navantia Ferrol, Spain. He is Head of the Area of Modeling & Simulation of the UMI Navantia-UDC. He holds an M.Sc. in Industrial Engineering from University of Vigo in the specialty of Industrial Management. He has led the development of projects related to industrial and logistical processes optimization in different shipyard construction. His email address is rmorgade@navantia.es.