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A HEURISTIC SIMULATION-BASED FRAMEWORK TO IMPROVE THE SCHEDULING OF BLOCKS ASSEMBLY AND THE PRODUCTION PROCESS IN SHIPBUILDING

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ABSTRACT

Strong global competition in the shipbuilding market has forced shipyards to focus their efforts on optimizing their system resources. Therefore, the development of efficient medium-term and short-term operation strategies in the shipyard block assembly process is becoming a potential competitiveness tool. This paper introduces a heuristic simulation-based approach to address the scheduling problem for shipbuilding in a real-world multi-stage production system. The main goal is to minimize the total production and assembly time of the shipbuilding process (makespan) applying different types of heuristic rules in an advanced simulation framework. The proposed simulation model allows evaluation of the effective production of a large number of blocks and sub-blocks, while satisfying a large set of hard constraints. Uncertain alternative scenarios are tested and computational statistics are carefully analyzed.

1 INTRODUCTION

Shipbuilding of large-scale vessels is a complex manufacturing process that is usually managed in a project-oriented approach. Each individual ship has some degree of customization and there are only few units based on the same design. However, in the last decades, efforts for applying Lean principles and standardizing processes have led to a modular approach (Zhang 2015). Nowadays shipbuilding companies use an integrated modular design to construct ships. Technological advances and more detailed planning allow the pre-fabrication of steel blocks or structures, which are then assembled in the so-called block erection process. Furthermore, different elements such as pipes, supports, and some electronic equipment are previously incorporated into the blocks. Hence, shipbuilding is carried out from subunits or modules that incorporate and integrate multiple systems. Under this approach, the common unit of production for most steps of the process is a block or sub-block.

The manufacturing process of shipbuilding begins with a block division step. Each block is different in size, type, and consists of one or several sub-blocks assembled, depending on the types of ships. A sub-block is composed of steel plates. The block division of a ship depends on the ship design. The representation of the construction in blocks is shown in Figure 1. In this case, the figure illustrates how two sub-blocks make up a block. In general, a ship is divided into many blocks of specific size.

Cho et al. (1998) point out that the block assembly process takes more than half of the total shipbuilding processes, so it is very important to have a practically useful block assembly process planning system which can build plans of maximum efficiency requiring minimum man-hours. For this reason, numerous researches have focused on improving the planning of shipbuilding using different perspectives. For instance, Seo et al. (2007) and Kim et al. (2002) model the problem of the block assembly planning as a constraint satisfaction problem where the precedence relations between operations are considered constraints. Many studies have used heuristic algorithms to improve long-term area utilization and minimize

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processing times of blocks in the planning of the shipbuilding process (Koh et al. 2008, Zhuo et al. 2012). Shang et al. (2013) proposed an allocation algorithm and mathematical model to optimize the block spatial scheduling. A research made by Xiong (2015) considered a hybrid assembly-differentiation flowshop scheduling problem and introduced a mixed integer programming (MIP) model to present some properties of the optimal solution. Mathematical models become very complicated due to the high computational complexity associated to the huge number of blocks and sub-blocks to be produced with finite shared resources.

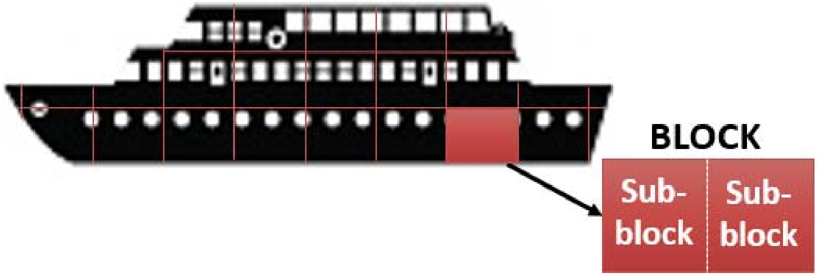


Figure 1: Method of division into blocks - Modular construction.

More recently, methods and simulation models have been proposed to solve the scheduling problem in shipbuilding. Cebral et al. (2016) and Liu et al. (2011) proposed a discrete-event simulation based model to achieve an efficient production planning and control. These approaches may be useful to propose heuristics based strategies to improve the effectiveness of shipbuilding process operations.

Following this direction, the present work aims at finding out an alternative solution approach of production and assembly operations in a multi-stage production system of a shipyard that can be used to minimize the expected makespan while all operations constraints are satisfied. A ship manufacturing system, which involves a series of production and assembly processes of block and sub-block for large-scale shipbuilding is considered. Hence, an advanced simulation model is proposed to represent and solve the scheduling problem aiming at minimizing the total processing and assembly time of blocks and sub-blocks (makespan) in the yard. Simio® software is the one selected for discrete-event simulation modeling.

Although rigorous mathematical optimization approaches may be used to find optimal/near optimal solutions to several challenging interesting problems, the problem representation must be usually simplified to avoid the significant computational effort that implies the realistic complex decision-making processes. In contrast to traditional scheduling tools, the simulation approach is based on a flexible custom-built simulation model of a complex system and is therefore highly flexible. In addition, its ability to deal with uncertainty and capture both the critical constraints and variations in the system makes it applicable to a wide range of scheduling applications. The simulation framework allows the easy development of sequencing rules including option such as: preferred order in resources requests, internal logic processes to add flexibility in each stage, and data table to create arrives of blocks. Hence, a simulation model is an ideal tool for production scheduling applications due to ability to generate a detailed resource constrained schedule adding the presence of uncertainty as well as a sensitive analysis tool to measure the impact of different factors in the system.

This paper is organized as follows. In Section 2, the block assembly process with all stages is described. The simulation model developed with the assumptions and heuristics proposed is presented in Section 3. Then, in Section 4, computational results from simulation study are presented. Finally, the conclusions are given in Section 5.

2 THE BLOCK ASSEMBLY PROCESS

In this section, we describe the procedure used for shipbuilding, based on blocks production and assembly. A block is a basic component used to construct a ship, which consists of one or more sub-blocks. Each sub-block is composed of small steel parts in accordance with the design drawing of the ship. Both blocks and sub-blocks are considered types of basic intermediate products in the modular design and construction.

In the block assembly process, sub-blocks are assembled in specific workshops to form large blocks. Next, the blocks are assembled in a dock to form the hull of the ship. Therefore, in the early stages of the shipbuilding process steel plates are processed to construct the sub-blocks. In the following stages, the blocks (assembled sub-blocks) are processed and assembled by a given sequence, respecting the specifications of ship assembly. The main stages of the shipbuilding process are illustrated in Figure 2 and are described below.

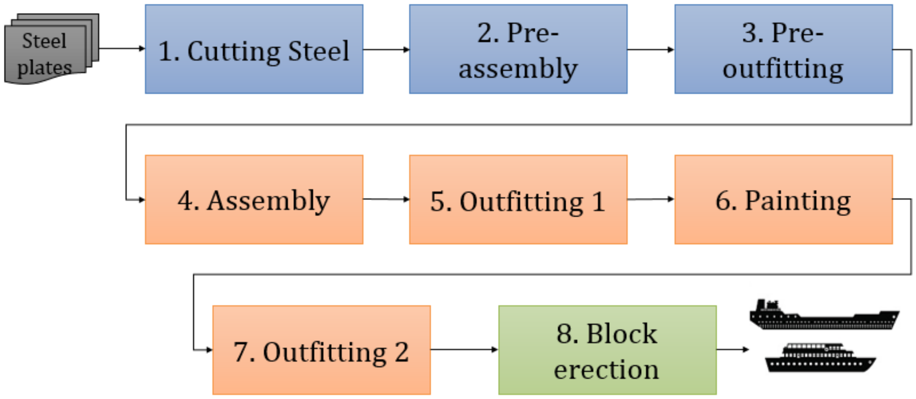


Figure 2: Shipbuilding process.

- *Cutting Steel:* the welding and cutting processes of steel plates are performed according to the requirements of the sub-blocks designs. Panels, sections, and assemblies are obtained as output from this stage.
- *Pre-assembly:* the small steel components fabricated in the previous process, as webs and panels, are assembled to form the sub-blocks using welding operations.
- *Pre-outfitting:* this process involves internally outfitting sub-blocks with items like pipes, brackets, and auxiliary components. Finished sub-blocks are obtained of this stage.
- *Assembly:* the blocks assembly consists of welding operations of sub-blocks to compose a specific block. The assembly process is carried out according to the specifications of each block.
- *Outfitting 1:* this process consists of installing pipes, and electrical and lighting lines inside blocks. Part of the outfitting work is performed when the ship is upside down. The objective is to facilitate material handing tasks.
- *Painting:* after assembling the sub-blocks to form blocks, they are painted in the painting booths. The protection and design requirements of blocks are considered in blasting and painting operations.
- *Outfitting 2:* the second outfitting process of blocks is performed after painting. All equipment that could be deteriorated in the painting process, for example electronic components, is installed at this outfitting stage of the shipbuilding process.
- *Block erection:* after the painting process and the installation operations of final equipment, prefabricated blocks are positioned in the dry dock to build the ship, and are assembled one after another. Welding operations are also used in this stage. There is a defined order to erect these

blocks, so if a block arrives earlier, it has to wait until its precedent is completed. Blocks have different times in this erection process according to the function it has: base block, lateral block or superior blocks.

3 SIMULATION MODEL

Discrete event simulation methods are adopted to represent the whole real-world process as an integrated form. Manufacturing and material handling provide one of the most important applications of simulation due to the complexity of the process. Managers have found it useful in providing "test drive" before making capital investments, without disrupting the existing systems with untried changes (Banks, 2005). Hussein et al. (2009) stated that in many cases the results of a simulation are a confirmation of expectations (system performance), but true benefit of simulation is the discovery of the unexpected situation or circumstance.

The shipbuilding process is a complex, long-term and stochastic process that requires coordination of many different critical shared resources. Hence, a simulation model is developed to determine the production planning for each stage of the system and find out the best configuration which allows minimizing the expected makespan. The simulation model allows analyzing and evaluating the dynamic behavior of the real-world system under study, considering different operative schemes, sequencing rules, uncertainty, and shared resource logics.

In this work, Simio® simulation framework is used to develop the DES model. It provides an object-based approach, which is a very natural and simple way to simulation modeling (Pedgen, 2009). A model is built by combining objects that represent the physical components of the system. The results given by the simulation model are then presented by user graphical interfaces that are particularly useful for the decision-making process. Moreover, Simio® provides a customized interface including the software planning necessary to get the most out of the facility under study as well as an user-friendly 3D graphical interface which allows obtaining a better visual experience to the world of simulation models. Figure 3 shows a global view of the model where most modules represent processing stages in the previous section.

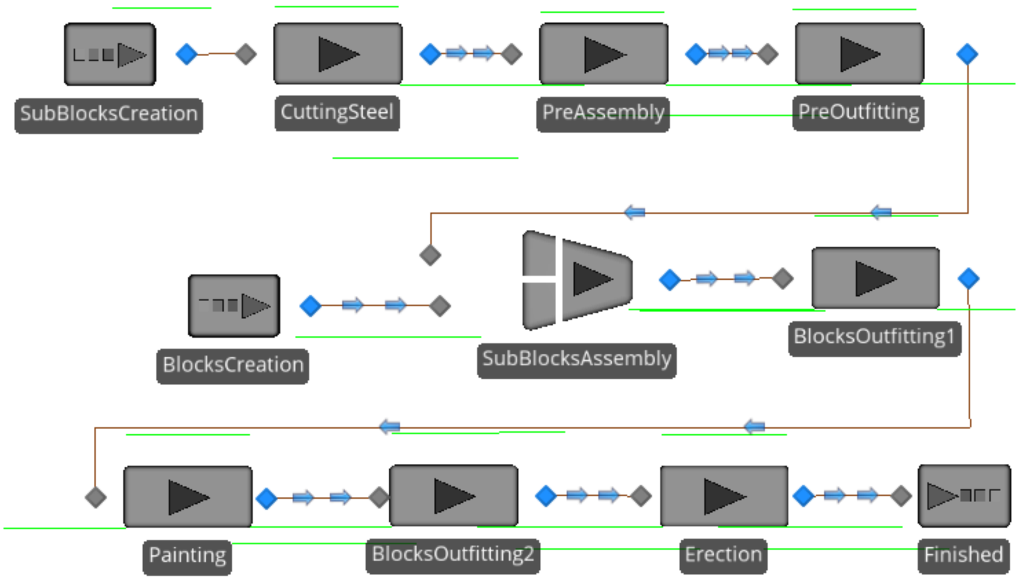


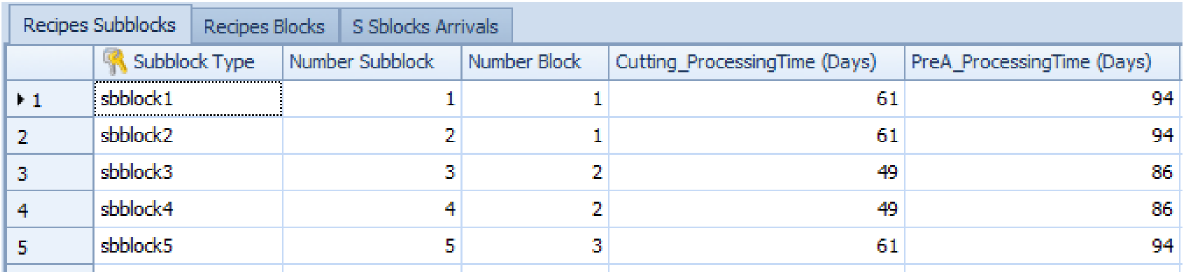
Figure 3: Simulation Model in Simio® 2D.

Due to confidentiality reasons, the real configuration of the lock assembly process, such as processing and assembly times, and the type or capacity of machines that considered, are not explicitly mentioned in this work. Therefore, the data shown below refer to a simplified model taken as an example. For instance, the Table 1 summarizes the characteristics of stages of a probable shipbuilding process.

Table 1: Configuration of shipyard workstations.

Stage (*s*)	*Name*	*Capacity*	*Entity to process*
1	Cutting Steel	2	Sub-blocks
2	Pre-assembly	6	Sub-blocks
3	Pre-outfitting	3	Sub-blocks
4	Assembly	6	Blocks
5	Outfitting 1	3	Blocks
6	Painting	2	Blocks
7	Outfitting 2	3	Blocks
8	Erection	1	Blocks in a defined order

Processing times vary depending on the block or sub-block and the stage. In the simulation model, tables are defined for these two types of entities determining processing times on each stage. Several stages present a stochastic behavior with probability distributions, principally normal and discrete ones. Figure 4 is an example of the table for sub-blocks.



	Subblock Type	Number Subblock	Number Block	Cutting_ProcessingTime (Days)	PreA_ProcessingTime (Days)
1	sbblock1	1	1	61	94
2	sbblock2	2	1	61	94
3	sbblock3	3	2	49	86
4	sbblock4	4	2	49	86
5	sbblock5	5	3	61	94

Figure 4: Sub-block recipes and processing timetable.

As mentioned before, there are not intermediate buffers between stages, but their capacities can be used to process or to store parts until the next stage has capacity available. In the model, this is restricted by using internal logic processes. This tool is useful to include more customization in objects behavior. It has logic steps with different functions such as assigning values to different variables or writing into an external file. Figure 5 presents internal logic processes associated to the *Painting* stage. These processes principally reserve resources to avoid been occupied when an entity is waiting to enter the next stage. They also write on an Excel file, which entities are entering or going out, and the time it is happening to posterior analysis. The only stage that does not accomplish this restriction is the *Pre-Assembly* one. We assume that its capacity is double, because sub-blocks are entering and blocks are going out. Therefore, the *Block-Erection* stage has bigger capacity because all blocks can wait to be assembled there.

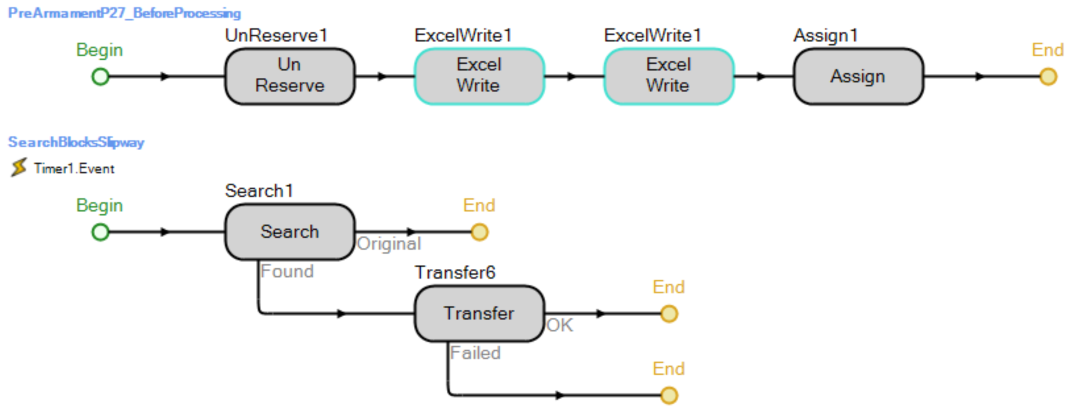


Figure 5: Internal logic processes for "Pre-assembly" and "Outfitting 1" stage.

3.1 Model assumptions

The shipyard could be considered a multi-stage and multi-product plant where the parallel units in each stage are identical. We assume the following hypotheses for the process described above:

- There are two types of products (or entities) in the shipyard: sub-blocks (formed by steel panels and open units) and blocks (formed by one or more sub-blocks).
- A unit (or workshop) cannot process more than one block (or sub-block, as appropriate) at a time. In other words, each workshop has capacity to process one block at a time.
- More than one unit cannot process a single block (or sub-block) in each stage.
- Processing units do not fail and processed blocks (or sub-blocks) are always satisfactory. The stops due to failures or sets up are not taken into account.
- Each block is made up of two known sub-blocks.
- The assembly sequence on slipway (the last stage of the line) is known a priori.
- The start of the current scheduling period is zero time.
- All units can start processing at time zero.
- There are shared resources between processing stages, i.e. there are resources that can be used in more than one stage.
- The processing times of each block are known a priori.
- Transfer times of the blocks (or sub-blocks) between the workstations are considered negligible.
- Raw materials are unlimited.
- Intermediate storage between stages is considered *NIS* (non-intermediate storage).

3.2 Verification and validation

Once the simulation model is finished, verification is carried out. Verification is concerned with determining if the conceptual model with its specifications and assumptions were correctly transformed into a computerized representation (Law, 2007). To verify the simulation model several requirements concerning expected values and system behavior were determined and compared. Each point is also analyzed in the simulation model looking if the same activities are being performed, initiating or finalizing in all stages. We obtained satisfactory conclusions.

Therefore, the model must be validated, determining how closely the simulation model represents the real system (Law, 2007). To attain this aim, several comparisons are made with information given from the shipyard, related to stages characteristic such as capacity, inventory policies, processing times. All aspects were discussed with experienced staff and historical information and necessary adjustments were made to achieve the desired values.

4 EXPERIMENTAL DESIGN AND RESULTS

After having performed an exhaustive verification and validation of the simulation model developed, an experimental design was defined and analyzed. The configuration of a real ship was evaluated in this experimentation process. However, due to confidentiality reasons, the real problem data was omitted in this paper. Instead, a representative case study with modified data is proposed. The aim was to present a shipbuilding process with a similar behavior to the real block assembly process, avoiding showing the real data such as time values, time units and capacity of each stage.

The experimental design performed was focused on examining results and proposing different configurations to improve the response variables of the model: (i) makespan of the global assembly process, (ii) utilization rates of each stage of the process, and (iii) waiting time of sub-blocks and blocks.

A bottleneck analysis was carried out by running the simulation model and the critical stage was clearly identified by testing reports and visual inspection. The Figure 6 shows an example of the utilization rate of each stage of the block assembly process. Note that stages *Cutting Steel* and *Painting* present the highest utilization rates. The first one causes a large queue at the beginning of the assembly line producing less use in the following stages.

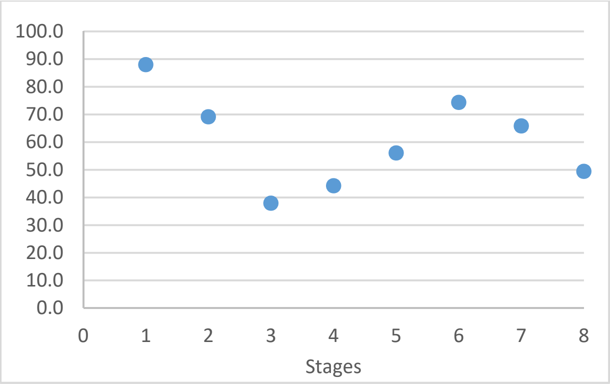


Figure 6: Utilization graph of shipbuilding stages.

The first proposal was to generate heuristics to order sub-blocks arrivals to the first stage of the block assembly line. The following heuristics are proposed:

1. Conventional order: sub-blocks arrive to the system and begin to be processed in the same order that then will be finally assembled in the dry dock (*Block-Erection* stage). The order of arrival of sub-blocks is as follows: *1, 2, 3, …, n*.
2. Inverting the order of arrival of sub-blocks from a same block. Blocks continue arriving in the conventional order to the *Block-Erection* stage, but sub-blocks from a same block are inverted order comparing to the first heuristic. For instance, order *i*: *2, 1, 4, 3, 6, 5*.
3. Inverting conventional order of the blocks.
4. *Global Shortest Processing Time* (SPT) for sub-blocks in the first stage. Sub-blocks are ordered starting with the one having the shortest processing time, and finishing with the one having the longest one.
5. SPT applied in large groups of sub-blocks, for example 22 sub-blocks. Then, each group of sub-blocks are ordered following the SPT heuristic.

6. SPT applied in short groups of sub-blocks. For example, groups of 11, 6, 4 and 3 sub-blocks.

The second proposal was to analyze the capacity of downstream bottleneck stages. Note that, as mentioned earlier, there are some stages sharing resources, i.e. there are sets of resources that can be used in more than one stage. For instance, *Pre-assembly* and *Assembly* stages share 12 resources divided equally, and *Pre-outfitting* and *Outfitting 1* stages share 6 resources. Hence, different combinations can be tested to evaluate resources usage in each stage.

The experimental design was performed considering all possible values of control variables to represent feasible scenarios of the shipbuilding process. The aim of the experimentation step is to analyze the influence that these variables have over response variables, and to provide a capacity and sequencing order to minimize the expected makespan. Therefore, a balanced assembly shipbuilding line is obtained with reduced assembly time and consequently reduced costs for the company. Table 2 presents the most significant factors and their levels used in the experimental design.

Table 2: Factors of the experimental design.

Factor	*Name*	*Levels*	*Factor type*
1	Sequencing rule	1. Conventional order 2. Inverting sub-blocks 3. Global SPT 4. SPT in groups of 22 sub-blocks 5. SPT in groups of 11 sub-blocks 6. SPT in groups of 6 sub-blocks 7. Inverting conventional order 8. SPT in groups of 4 sub-blocks 9. SPT in groups of 3 sub-blocks	Qualitative
2	Quantity of resources in stage 2 (and on its complementary stage)	5 in stage 2 (7 in stage 4) 6 in stage 2 (6 in stage 4) 7 in stage 2 (5 in stage 4)	Quantitative
3	Quantity of resources in stage 3 (and on its complementary stage)	2 in stage 3 (4 in stage 5) 3 in stage 3 (3 in stage 5) 4 in stage 3 (2 in stage 5)	Quantitative

After executing the simulation model with all different feasible configurations a sensitive analysis was performed. The mean and confidence interval for each scenario were calculated considering ten replications. Taking into account the control variables such as the quantity of shared resources for the complementary stages and the sequencing rules for the first stage, a statistical treatment of data was carried out. Therefore, an ANOVA analysis was performed.

According to the results obtained, factors that have greatest influence on the makespan are the factor 1 and 2: the sequencing rules and the quantity of resources of the second stage (includes variation on its complementary stage, *Pre-assembly* and *Assembly* stages). Neither variations on the combination of resources assigned to *Pre-outfitting* and *Outfitting 1* stages (factor 3) or interaction between different factors are considered significant. Hence, these last control variables do not affect the expected makespan response.

Confidence intervals for every combination of significant factors presented in the Table 2 are shown in the Figure 7. In the vertical axis there are two numbers: the first one represents the quantity of resources in the second stage and the second one represents the sequence rule, i.e. factor 1 and 2 respectively. The horizontal axis contains makespan values. A clear difference between sequencing rules 3 and 7 can be easily observed, having the worst makespan confidence intervals. On the other hand, five shared resources in factor 2 (between stages 3 and 5) seem to be the worst choice. Although there is not a clear difference between every level of each factor, the first sequencing rule (conventional order) seems to obtain better results than other ones.

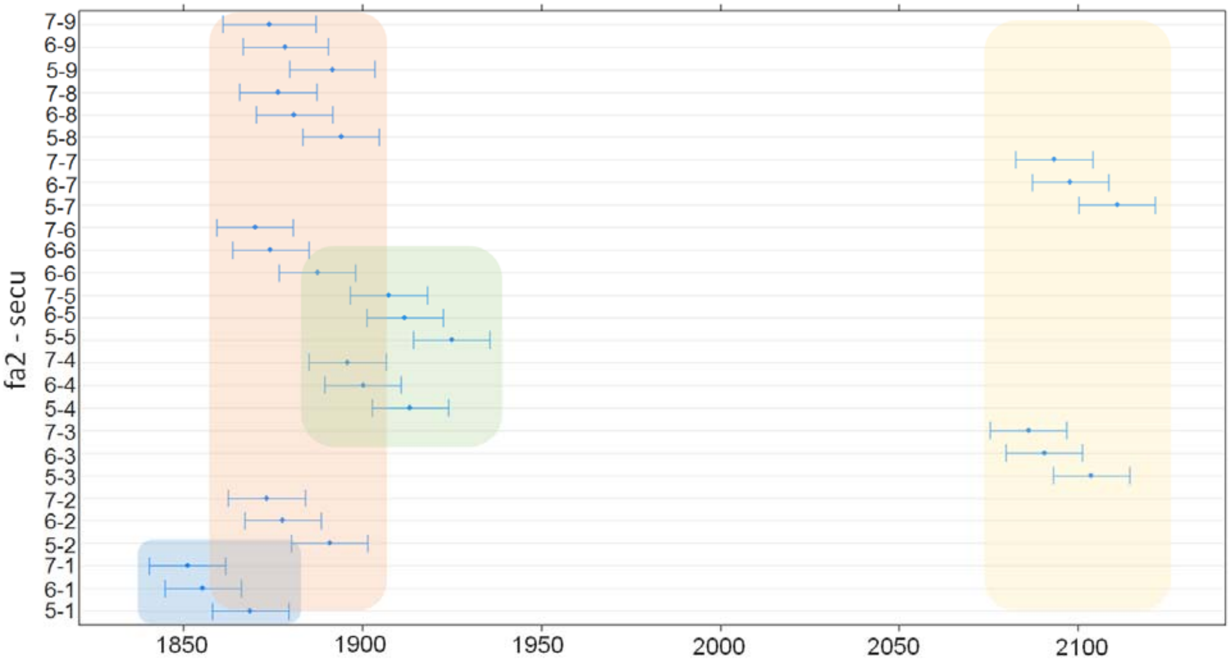


Figure 7: Confidence intervals for all combinations of significant factors (1 and 2).

Multiple comparisons for both significant factors were made using Tukey to empathize the analysis and find robust conclusions. Consecutively, Figure 8 and Figure 9 represent confidence intervals obtained from the difference between levels of each factor.

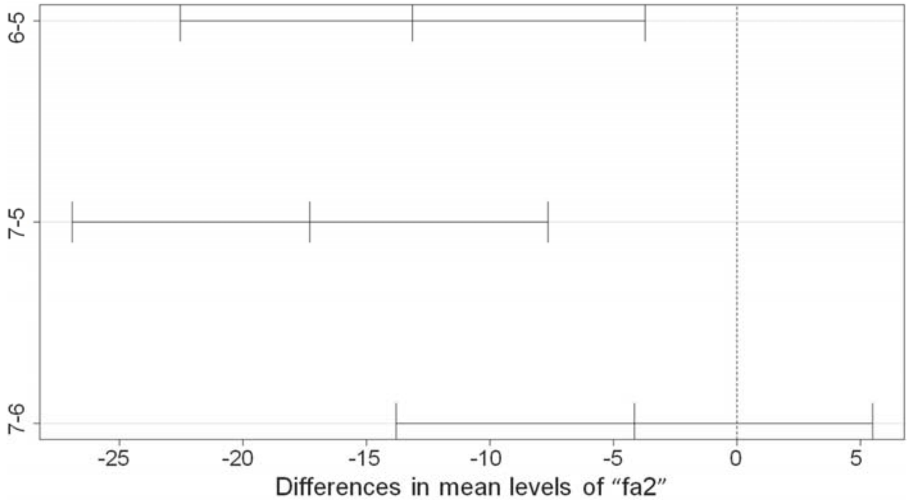


Figure 8: Confidence intervals for multiple comparisons of factor 2.

According to the Figure 8, we can conclude that the use of 5 resources in the *Pre-assembly* stage of the 12 resources available for both complementary stages (*Pre-assembly* and *Assembly)* have a negative impact on makespan. Nonetheless, there is no sufficient evidence to assume that assigning 7 resources is better than 6 to improve the expected makespan.

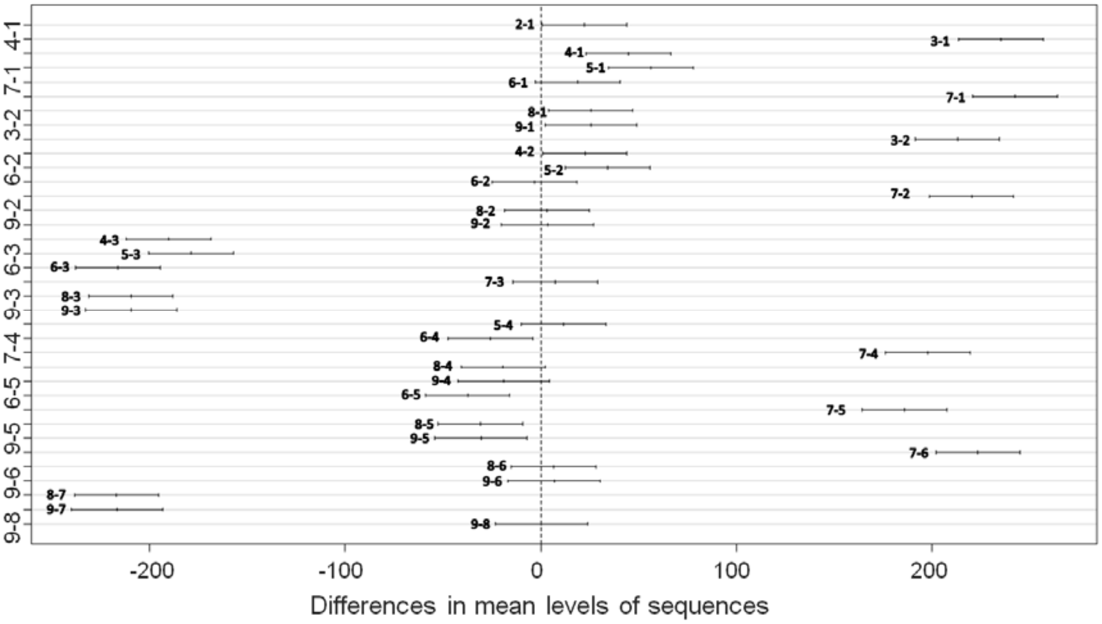


Figure 9: Confidence intervals for multiple comparisons of factor 1.

Analyzing Figure 9, the conventional sequence (level 1 of factor 1) could be considered the best sequence rule. However, also level 6 (SPT in groups of 6 sub-blocks) could be assumed to reduce the expected makespan due to its confidence interval include the zero-value (but almost in the end). Then, levels 2, 6, 8, and 9 did not present a significant difference to assume that one is better than the other. All these sequencing rules are related to small-groups heuristic application up to 6 sub-blocks per group. The following levels, 4 and 5, presented a pronounced difference with the above mentioned levels, but were similar between them. These are the two sequencing rules that use big groups to apply SPT. Finally, the worst sequencing rules were, as expected, level 3 and 7, using global SPT and inverted conventional order respectively.

On the one hand, SPT heuristics seem to be efficient when are applied for small groups of sub-blocks. However, the best solution found was the conventional order used to perform the final block-erection process. Although other configurations reduce the makespan up to the *Outfitting 2* stage, the rule of the conventional order allows to avoid queues in the last stage of the shipbuilding process. Future researches could focus on alternative orders to carry out the erection process and reduce these the last queues. Note, the SPT heuristic applied in large groups of the sub-blocks would delay the arrival of early sub-blocks required in the last stage and the rest of them would need to wait.

On the other hand, the variation of the amount resources shared between stages only impact in the solution when are made on the *Pre-assembly* and *Assembly* stages (factor 2). This mean that add more resources in the *Pre-assembly* stage (and less resources in its complementary stage) would improve the expected makespan.

As an example, Figure 10 shows the schedule of the case study proposed with 10 blocks and 20 sub-blocks. To improve this schedule, future research could face the last stage, the block-erection process, to find alternative orders required to blocks arrivals to this stage.

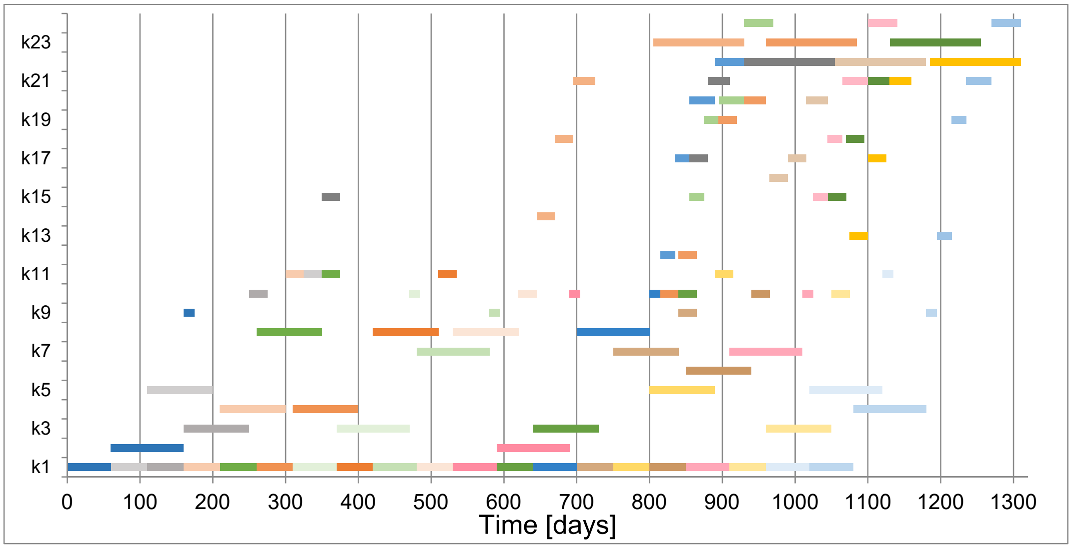


Figure 10: Solution schedule of case study proposed.

5 CONCLUSION

A discrete event simulation model was developed to evaluate a complex block assembly process of a naval industry. This type of the problem requires big efforts for generating the production plan due to considerable number of blocks and sub-blocks, and resources involved in the shipbuilding process. Several heuristic rules based on the preliminary results obtained are proposed to improve the system efficiency. An experimental design is performed considering these heuristics for the sequencing order of the blocks for the bottleneck stage, shared resources between specific stages, and possible combinations between these factors. Different scenarios are tested in order to find the best configuration in terms of makespan and utilization rate. Output results demonstrate that several configuration of the system allow to balance the use of shared resources and reduce the expected makespan. Hence, the simulation model is a practical tool that could be used to obtain an efficient solution of real world complex scheduling problem.

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