A HYBRID SIMULATION-BASED OPTIMIZATION APPROACH FOR SCHEDULING DINAMIC BLOCK ASSEMBLY IN SHIPBUILDING

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ABSTRACT

Shipbuilding is a complex and long-term process which requires the coordination of a large amount of resources and several types of manufacturing process planning. To achieve scheduling optimization of block production line and therefore, greater competitiveness in shipbuilding market, an efficient medium-term and short-term operations strategies are used. This work focuses on a real-world case study involving a large amount of blocks. Hence, a novel simulation-based optimization approach is developed for the efficient scheduling of production and assembly operations in a system of multi-stage multi-product production of a shipyard. The goal is to generate good schedules with modest computational effort minimizing the makespan (the total processing, waiting, and assembly time) while satisfying a large set of hard constraints. Mathematical model results are generated by using data from a real shipyard and improved through the simulation. Several examples are solved and reported to illustrate the capabilities of the approach proposed.

Keywords: discrete-event simulation, scheduling, shipbuilding, continuous time-slot, MILP model

1. INTRODUCTION

The management of workshops in a shipyard requires spatial and resource restrictions. Each ship has a high degree of customization and there are few units having a similar design. Shipbuilders have considered the assembly and production process as a bottleneck since every panel for every ship has to be processed through a set of workshops and unexpected uncertainties. Hence, the shipbuilding process involves a largest amount of work and many decisions.

Lee et al. (2009) point out that shipyards use a conveyer line production system with a combination of human and automatic equipment resources at the panel assembly workshop promoting the efficiency of conventional management and predictive planning. Nonetheless, this management has not allowed satisfactory results in terms of productivity. Therefore, in the last decades, a modular approach has been considered applying Lean principles and standardizing processes to improve the productivity of the shipyard shop (Cebral-Fernandez et al. 2016). A modular design has been developed allowing the pre-fabrication of steel blocks or structures, which are then assembled in the block erection process. According to this approach, the common unit of production for most steps of the process is a block or sub-block.

Furthermore, Cho et al. (1998) highlight that the block assembly process takes more than half of the total shipbuilding processes. Hence, it is essential to have a useful block assembly process planning system which allows building plans of maximum efficiency requiring minimum man-hours. Following this purpose, the main objective of the present work is to find an optimal or near optimal solution for the scheduling problem on a shipbuilding production and assembly process. This process involves multi-stage production system with variable processing times for each module and strong storage restrictions.

To achieve the aim, simulation and optimization tools have been evaluated to generate an optimal schedule. On the one hand, simulation technology has been used in shipbuilding problems in several works involving different aspects such as the spatial scheduling problem (Liu et al. 2011); data-based simulation model generation (Back et al. 2016); dynamic effects for design step (Park et al. 2016); and the assembly scheduling problem using heuristics (Lee et al. 2009, Chen et al. 2013).

On the other hand, mathematical optimization models and algorithms were applied to solve scheduling problems. 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. To optimize the block spatial scheduling, Shang et al. (2013)present an allocation algorithm and mathematical model. Different methods and algorithms have been proposed recently to solve the scheduling problem in shipbuilding from different approaches, but they do not ensure an optimal solution of the scheduling problem. A research made by Xiong et al. (2015) consider a hybrid assembly-differentiation flowshop scheduling problem and introduce a mixed integer programming (MIP) model to present some properties of the optimal solution. This approach could be useful

to the shipbuilding issue due to it could also be considered an assembly flowshop scheduling problem.

In previous work, a mixed integer linear mathematical formulation (MILP) has been considered to efficiently solve the scheduling problem up to ten blocks (Basán et al. 2017). The mathematical models developed present an increased computational complexity associated to the big number of blocks and sub-blocks and the possible combinations which this type of real-world scheduling problem involves. Hence, a new hybrid simulation and optimization approach is proposed to solve the scheduling problem aiming at minimizing the makespan of blocks and sub-blocks in the yard. Several MILP formulations are used and their results are combined to become an input into a discrete-event simulation model. The MILP model is based on continuous time-slot concept. GAMS® is the software chosen for mathematical modeling and Simio® software is the one selected for discrete-event simulation.

This paper is organized as follows. In Section 2, the block assembly process with all stages is described. Then, Section 3 contains the proposed solution methodology. The mathematical model developed with assumptions and nomenclature is presented in Section 4, and the simulation model in Section 5. Next, in Section 6, computational results obtained of the hybrid simulation-based optimization approach are shown. Finally, conclusions are given in Section 7.

2. THE BLOCK ASSEMBLY PROCESS

The manufacturing process of shipbuilding is based on blocks production and assembly. Hence, this process begins with block division. A block is a basic component in the ship construction which varies in size, type, and consists of one or several sub-blocks assembled, depending on type of ship. A sub-block is composed of steel plates in accordance with the design drawing of the ship.

Therefore, the block division in shipbuilding process depends on the ship design. A ship is usually divided into many blocks of specific size and these, in turn, can be divided into same sub-blocks. Both blocks and subblocks are considered types of basic intermediate products in the modular design and construction. Figure 1 illustrates an example of the method of division into blocks and sub-blocks.



Figure 1: Method of division into blocks - Modular construction

Following is the steps involved in the block assembly process. As shown in the Figure 2, in the early stages of the shipbuilding process, sub-blocks are processed and assembled in specific workshops to form large blocks. Then, in the following stages, the blocks are assembled in a dock to form the hull of the ship.



Figure 2: Shipbuilding process

The first stage of the block assembly process is *Cutting Steel*. This stage begins with reception of steel sheets and profiles. Then, these elements are cut into small parts and assembled to form small units according to the requirements of the sub-blocks designs. As result of welding and cutting processes panels and webs are obtained that will constitute the structural components of the blocks.

In the following step, *Pre-assembly*, welding operations are used to assembled the small structural elements and, therefore, formed the sub-blocks. Then, in the *Pre-outfitting* stage, different components as pipes, brackets and auxiliary elements, are installed in each sub-block. Hence, completed sub-blocks are obtained from this outfitting process.

The next step of the shipbuilding process is the assembly to sub-blocks (*Assembly*). According to the specifications of each block, the sub-blocks are positions together to carry out welding operations and form the blocks. Then, outfitting process is performed to install pipes, and electrical and lighting lines inside blocks (*Outfitting 1* stage).

Once the sub-blocks have been assembled and equipped, are blasted and painted in the painting booths. In this *Painting* stage the protection and design requirements of blocks are taken into account.

After painting process, all equipment that could be deteriorated in this process, such as wires and electronic components, is installed at the *Outfitting 2* stage. Therefore, a second outfitting process of blocks is performed before are moved to the dock.

The last stage is *Block erection*, where the prefabricated blocks are positioned in the dry dock to build the ship. The erection process consists of assembling the blocks, one after another, by a pre-established sequence, respecting the specifications of the ship. In accordance with given sequence, if a block arrives earlier, it must to

wait until its precedent is completed. There are different processing times in this step depending on the type of block being assembled (base block, lateral block or superior block). Figure 3 shows these different erection times between the lateral and superior blocks.



Figure 3: Block erection processing times

A possible workshop configuration of a shipyard is presented in Table 1. Note that capacity and processed product are described in each stage detailed above. This configuration belongs to the case study addressed in this work and is based on a real world problem. The data shown below refer to a simplified model due to confidentiality reasons. Hence, the real configuration of the block assembly process is not explicitly mentioned.

T 1 1 1 0

Table 1: Stages						
Stage	Capacity	Entity to process				
Cutting Steel	2	Sub-blocks				
Pre-Assembly	6	Sub-blocks				
Pre-Outfitting	3	Sub-blocks				
Sub-blocks Assembly	6	Sub-blocks				
Blocks Outfitting 1	3	Blocks				
Painting	2	Blocks				
Blocks Outfitting 2	3	Blocks				
Erection	1	Blocks in a defined order				

3. PROPOSED SOLUTION METHODOLOGY

This work introduces an algorithm to generate a complete schedule of shipbuilding process incorporating a mixed-integer linear programming continuous time-slot formulation and a discrete-event simulation model. The MILP model developed uses sequencing variables for the processing and assembling tasks keeping the complexity at a manageable level.

Moreover, an efficient discrete-event simulation framework is developed to represent the assembly operations in a system of multi-stage production of ships in a shipyard. The major advantage of this computer-aided methodology is the possibility of reproducing highly complex manufacturing process in an abstract and integrated form, visualizing the dynamic behavior of its constitutive elements over time (Banks et al. 2005). Figure 4 presents a brief description of how the GAMS® model and Simio® model are associated to obtain a final result.



Figure 4: Steps of the solution methodology

Note that mathematical models find difficulties to converge into a solution in this kind of problems including a large amount of blocks and sub-blocks. The reason is that possible combinations increase with every additional block. Hence, several iterations are carried out to allow the solution of this large-scale problem in reasonable time. Each iteration represents a constrained version of the global model given in the following section. As a result, the MILP model generated achieves an effective solution for the whole shipyard scheduling problem. It also becomes useful for making and testing alternative decisions to enhance the current process performance. Castro et al. (2011), uses a similar hybrid simulation optimization approach to address a similar scheduling problem.

On the other hand, predefined job-sequences obtained from the set of optimization-based formulations combined are used to create an input to the simulation model. In other words, these sequences are generated by MILP model and written in Excel as input data to the Simio® model.

The simulation model structure allows easily, by using tables, change arrival sequences of sub-blocks to the system according to the output of mathematical models defined. Multiple runs are performed and written in Excel to generate statistical data as output data.

Therefore several scenarios are defined changing the quantity of blocks to enter as an input into the mathematical model, simulate the chained sequence results and compare computational effort and solutions. The aim is to analyze the impact that industrially size problems has on solutions obtained from the interaction of a mathematical and simulation models.

4. MATHEMATICAL MODEL

In order to develop an efficient mathematical formulation all production and assembly operations and the described characteristics of the shipbuilding problem are taken into account. The block assembly process requires coordination of many different resources. Hence, it is a complicated and long-term process.

Following is mathematical model based on the continuous time-slot batches concept to optimize the

processing sequence of the blocks at each stage and, therefore, minimizing the total processing time. The shipyard is considered a multi-stage and multi-product plant. The nomenclature used in the model and all constraints involved, including the objective function, are detailed in this section.

Considerer the shipbuilding system in Figure 2, where a set J of sub-blocks must be processed and assembled to form then a set I of blocks. These blocks must also be processed and then assembled in the dock. A total of S stages are considered with K_s identical parallel units. Let K denote the number of units (or workshop) in the shipyard.

Note that there are two types of products in the shipyard: sub-blocks (j = 1, 2, ..., m) and blocks (i = 1, 2, ..., n), assuming that each block is made up of two known sub-blocks. Although each product has its own requirements, follows the same sequence 1, 2, ..., c of processing stages, where $s \in S$.

Moreover, each workshop has capacity to process one block (or sub-block) at a time and, likewise, more than one workshop cannot process a single block in each stage. In addition, each workshop servers as intermediate storage if processing finished and the next step is not yet available.

Processing times of each block are known a priori $(TP_{j,s})$ and $TPb_{i,s}$, and transfer times between the units are considered negligible.

The assembly sequence on slipway (*Erection* stage) is known a priori. In addition, the output order of finished blocks of *Outfitting 2* stage is the same order in which they will be assembled in the last stage of shipbuilding process. Hence, the MILP model proposed determines the production schedule until the *Outfitting 2* stage.

Sets

- Iset of blocks (index i, i = 1, 2, ..., n)Jset of sub-blocks (index j, j = 1, 2, ..., m)Sset of stages (index s, s = 1, 2, ..., c)
- *K* set of machines (index k, k = 1, 2, ..., q)
- *P* set of slots (index p, p = 1, 2, ..., m)
- J_i set of sub-blocks of each block i
- K_s set of parallel machines in stage *s*
- I_s set of blocks that can be processed in stage s
- J_s set of sub-blocks that can be processed in stage s

Parameters

$TP_{j,s}$	processing time of sub-block i at stage s
TPb _{i,s}	processing time of block i at stage s
mcs	parallel units in stage s
М	big constant in big-M constraints

Continuous variables

Ti _{j,s}	initial processing time of sub-block <i>j</i> in stage <i>s</i>
$Tf_{j,s}$	final processing time of sub-block <i>j</i> in stage <i>s</i>
Tbi _{i,s}	initial processing time of block <i>i</i> in stage <i>s</i>
Tfb _{i,s}	final processing time of block i in stage s
$TSi_{p,k}$	initial processing time of slot p in machine k
$TSf_{n,k}$	final processing time of slot p in machine k

mk makespan

Binary variables

 $x_{j,p,k,s}$ 1, indicates whether sub-block *j* is processed in position *p* of machine *k* of stage *s*

 $y_{i,p,k,s}$ 1, indicates whether block *i* is processed in position *p* of machine *k* of stage *s*

Constraints

The block assembly system in a shipyard involves several types of constraints such as resource, allocation, sequencing, and timing constraints. Therefore, all these must be taken into account in the mathematical model to determine the optimal production scheduling.

Firstly, the objective function of the MILP model is defined in the equation (1): makespan minimization.

min
$$mk$$
 (1)

Due to the early stages of the shipyard process subblocks and the last ones process blocks, two binary variables were defined to formulate allocation constraints: $x_{j,p,k,s}$ and $y_{i,p,k,s}$. The first of these is used to determine which unit processes each sub-block in the first three stages. And the last of these defines which unit is used to process and assembly each block of ship. Hence, equations (2)-(7) use these binary variables to introduce the allocation constraints. Equations (2) and (3) are constraints assigning sub-blocks and blocks to units of each stage of shipbuilding, where each product (sub-block and block) must only be processed in one workshop of each stage. And equations (4) and (5) are constraints assigning slots to sub-blocks or blocks in each unit of step s, i.e. these equations assign only one sub-block (or block) in each slot of each workshop.

$$\sum_{p=1}^{N} \sum_{k=1, k \in K_{s}}^{mc_{s}} x_{j, p, k, s} = 1 \quad \forall j \in J, s \in S, s \leq 3$$
(2)

$$\sum_{p=1}^{N} \sum_{k=1,k \in K_{s}}^{mc_{s}} y_{i,p,k,s} = 1 \quad \forall i \in I, s \in S, s > 3$$
(3)

$$\sum_{j=1}^{M} x_{j,p,k,s} \le 1 \quad \forall p \in P, k \in K_s, s \in S, s \le 3$$
(4)

$$\sum_{i=1}^{N} y_{i,p,k,s} \le 1 \qquad \forall p \in P, k \in K_s, s \in S, s > 3$$
 (5)

$$\sum_{j=1}^{M} x_{j,(p+1),k,s} \le \sum_{j'=1}^{M} x_{j',p,k,s} \forall p \in P, k \in K_s, s \in S, s \le 3, j \neq j'$$
(6)

$$\sum_{i=1}^{N} y_{i,(p+1),k,s} \leq \sum_{i'=1}^{N} y_{i',p,k,s} \forall p \in P, k \in K_{s}, s \in S, s > 3, i \neq i'$$
(7)

Equations (8)-(12) introduces the sequencing constraints, where equations (8)-(10) state the processing order of products at each stage identifying those that process sub-blocks, blocks or both products. Moreover, slots must also be sequenced in each unit (eq. 11).

$$Tf_{j,s} \le Ti_{j,(s+1)} \quad \forall j \in J, s \in S, s < 3$$
(8)

$$Tbf_{i,s} \le Tbi_{i,(s+1)} \quad \forall i \in I, s \in S, s > 3$$
(9)

$$Tf_{j,s} \le Tbi_{i,(s+1)} \quad \forall i \in I, j \in J_i, s \in S, s = 3$$
(10)

$$TSf_{p,k} \le TSi_{(p+1),k} \quad \forall k \in K, p \in P$$
(11)

In the last stage of shipbuilding process (*Block erection*) a predefined block assembly sequence must be satisfied according to specification of the Figure 3. Therefore, Equation (12) is introduced to fulfill this given sequence.

$$Tbf_{i,s} \le Tbf_{i+1,s} \quad \forall i \in I, s \in S, s = |S|, i < |I| \quad (12)$$

The duration of product i or j in stage s must be equal to initial processing time plus the processing time at that stage (eq. 13-14). Similarly, the sum of start processing time of slot p in step s and processing time of product assigned to that slot must be equal to final processing time of the slot (eq. 15-16).

$$Tf_{j,s} = Ti_{j,s} + \sum_{p}^{N} \sum_{k \in K_{s}} x_{j,p,k,s} * TP_{j,s}$$
$$\forall j \in J, s \in S, s \leq 3$$
(13)

$$Tbf_{i,s} = Tbi_{i,s} + \sum_{p}^{N} \sum_{k \in K_{s}} y_{i,p,k,s} * TPb_{i,s}$$
$$\forall i \in I, s \in S, s > 3$$
(14)

$$TSf_{p,k} = TSi_{p,k} + \sum_{j}^{M} x_{j,p,k,s} * TP_{j,s}$$
$$\forall p \in P, k \in K_s, s \in S, s \le 3$$
(15)

$$TSf_{p,k} = TSi_{p,k} + \sum_{i}^{N} y_{i,p,k,s} * TPb_{i,s}$$
$$\forall p \in P, k \in K_s, s \in S, s > 3$$
(16)

The constant M is used in equations (17)-(20) to model the relationship between slots and blocks (or subblocks, as appropriate). If a sub-block (or block) is processed in position p of the of machine k of stage s (i.e. $x_{j,p,k,s} = 1$ or $y_{i,p,k,s} = 1$) then the start time of the slot *p* must match with the start processing of the subblock (or block).

$$-M(1 - x_{j,p,k,s}) \le Ti_{j,s} - TSi_{p,k}$$

$$\forall i, j \in J, p \in P, k \in K_s, s \in S, s \le 3$$
(17)

$$M(1 - x_{j,p,k,s}) \ge Ti_{j,s} - TSi_{p,k}$$

$$\forall i, j \in J, p \in P, k \in K_s, s \in S, s \le 3$$
(18)

$$-M(1 - y_{i,p,k,s}) \le Tbi_{i,s} - TSi_{p,k}$$

$$\forall i, i \in I, p \in P, k \in K_s, s \in S, s > 3$$
(19)

$$M(1 - y_{i,p,k,s}) \ge Tbi_{i,s} - TSi_{p,k}$$

$$\forall i, i \in I, p \in P, k \in K_s, s \in S, s > 3$$
(20)

Due to the makespan represents the total processing and assembling time required for the construction of a ship and the shipyard has a sequential processing, it could be calculated considering the longest final processing time of last stage of shipbuilding process.

$$mk \ge Tfb_{i,s} \quad \forall i \in I, s \in S, s > 3 \tag{21}$$

5. DISCRETE-EVENT SIMULATION MODEL

Simulation technology is a type of shipbuilding product lifecycle management solution used to support production planning or decision-making (Back et al. 2016). Banks et al. (2005) point out that a simulation model can be used to investigate a wide variety of "what if" questions about the real-world system. Potential changes to the system can first be simulated, in order to predict their impact on system performance. Thus, from the simulation, data are collected as if a real system were being observed. This simulation-generated data is used to estimate the performance variables of the system. In this work, the simulation model is used to combine the results of the mathematical models and obtain the expected makespan including stochastic variables. The groups of blocks are separately optimized to minimize their local makespan. The outputs of the mathematical models are optimal sequences of groups of blocks. By introducing these sets of sequences into the simulation model we can chain them to obtain a real time in the global production process. Therefore, it includes de Erection stage, where blocks are assembled following a defined order. This stage will also affect the global makespan.

In conclusion, simulating the outputs of the mathematical model allows adding more detail, obtaining more reliable results. Hussein et al. (2009) add that there are some cases where the results of a simulation are a confirmation of expectations, but the true benefit is the discovery of the unexpected situation or circumstance. The simulation could be useful to find if the *Erection* process affects optimal sequences and if different scenarios really make an impact on global makespan.

The chosen simulation framework for this study is Simio® software. Figure 5 presents a global view of the model where most modules represent processing stages.



Figure 5: Simulation Model in Simio® 2D

Storage restrictions are modeled using internal logic processes. These processes are sequences of steps with logical actions like assigning values to variables, using conditions to make decisions, waiting until an evet occurs, reserving or unreserving resources, etc. This tool allows to include more customization on system.

Figure 6 presents internal logic processes associated to the Painting stage. These processes principally reserve and unreserve resources to avoid being occupied when an entity is waiting to enter the next stage. They also write on worksheet output values to posterior analysis. The stages that do not accomplish this resctriction are Sub-blocks Assembly and Erectionones.



Figure 6: Internal logic processes for Painting stage

Processing times vary depending on the block or subblock and the stage. In the simulation model, tables are defined for these two types of entities determining processing times on each stage. Simio allows making data tables to hold model data and then they can be referenced by individual entities. The data can be any of the property types provided by software including expressions, object references, class types, etc. Hence, each entity in the model can reference a specific row of data in the table containing, for example, processing times. Data import and export can be used for both Data Tables and Sequence Tables. Figure 7 is an example of the table for sub-blocks. However, several stages present a stochastic behavior with probability distributions, principally normal and discrete ones. Distribution probabilities with their parameter values can be directly entered into processing time properties in module characteristics.

Views <	Redp	Recipes Subblocks Recipes Blocks					
		R Subblock Type	Number Subblock	Number Block	Cutting_ProcessingTime (Days)	PreA_ProcessingTime (Days)	
	+1	sbblock1	1	1	58	94	
Tables	2	sbblock2	2	1	64	94	
	3	sbblock3	3	2	40	86	
1	4	sbblock4	4	2	58	86	
Lookup Tables	5	sbblock5	5	3	59	94	
	6	sbblock6	6	3	63	94	
<u>188</u>	7	sbblock7	7	4	41	86	
Rate Tables	8	sbblock8	8	4	57	86	
-	9	sbblock9	9	5	42	86	
21	10	sbblock10	10	5	56	86	
Cabadudaa	11	sbblock11	11	6	55	94	

Figure 7: Sub-block recipes and processing times table

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 traduced in computerized representation (Law 2007). To verify the simulation model there is an iterative comparison between outputs of the GAMS® model and the Simio® model. The Gantt chart obtained as a result from the mathematical model is analyzed in different points of the timeline. 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. Validation is concerned with 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.

6. SCENARIOS AND RESULTS

Once mathematical and simulation models are developed, verified and validated, experimentation is performed. The first scenario considered is the one that has a set of 1 block (2 sub-blocks) for each MILP problem. Hence, there is no global optimization and blocks are processed in order from 1 to N. Next, the following scenario consists in adding 2 or 3 blocks to each group (following the conventional order) and running all MILPs generated. Following this logic, the sets of groups continue increasing and the number of MILP problems decreasing up to finding a set that cannot be solved in a reasonable computer time. Computational efforts are compared against solutions obtained. Table 2 summarizes results obtained from experimentation. It contains (i) the number of scenario, (ii) the quantity of sub-blocks per group; (iii) the quantity of MILP models to run on each scenario; (iv) the total computational time in days (CT); (v) the

makespan as a sum of MILP model outputs (MILP MK); and finally, (vi) the expected makespan obtained from simulation runs (EMK). The last column involves stochastic processing times and 10 replications per scenario.

Scenario	Group size	MILP models	СТ	MILP MK	EMK
1	-	-	-	-	3427.9
2	6	11	0.02	5561	3391.4
3	8	8	0.11	4802	3385.4
4	10	7	0.66	4642	3405.6
5	14	5	1.21	4194	3412.8
6	16	4	8.17	3940	3413.0
7	22	3	75.44	3855	3426.4

Table 2: Results

MILP MK is calculated only to have a reference value. As you can observe in Table 2, this makespan appears to be improving as the group size increases. A possible cause is that there are not determined initial conditions on each MILP model considering the previous set of sub-blocks processed previously (all resources are idle) and processing times used are deterministic.

The best scenarios according to the expected makespan are the second and third ones, which involve optimization in small groups. The worst results includes the conventional order, and those scenarios having bigger size of sets. Nonetheless, variations in makespan values are small, and this results could vary due to the stochastic nature of the problem. Figure 8 presents both makespan results on the left axis values and the computational time involved on the right axis.



Figure 8: Makespan vs Computational Time

On the one hand, when simulating chained sequences resulting from MILPS per scenario, including stochastic processing times and block-erection last stage, the makespan obtained is more reliable than the simple sum of MILP model outputs. Expected makespans have a maximum variation of days of 2 %. Thus, scenarios do not provide significant differences between them. Nonetheless, the computational time has an important increasment rate on each scenario. In conclusion, when increasing group sizes, computational times strongly increases but solutions do not proportionally improve. Figure 9 shows resulting boxplots of each scenario (1 to

7). No significant differences can be observed. Therefore, an ANOVA test is performed to identify if there is a significative difference between scenarios considering individual makespans from all replications. The result was a p-value of 0.21, discarting a possible best solution. However, in Figure 9, despite of the similarity between all boxplots, it is possible to identify that, from second to seventh scenario, results tend to get worse, and the worst is the first one. Scenario 2 and Scenario 3 seem to have better results.



Figure 9: Output variable boxplot per scenario

CONCLUSIONS

A hybrid simulation-optimization approach was developed to solve the scheduling problem of a complex block assembly process of a naval industry. This realworld case study involves a considerable number of blocks and sub-blocks, requiring important efforts for generating the production plan. A combination between a set of MILP models and a discrete-event simulation model was performed to obtain the best processing sequence to improve the system efficiency. MILP models contribute to find optimal sequences for groups of blocks, and simulation provides a more reliable solution taking MILP outputs adding stochasticity and the block-erection process. Different scenarios were proposed and computational experiences were measured, comparing computational time vs solution improvement. Results demonstrate that computational time strongly increases without providing much better solutions. Hence, the major advantage of this tool is that it could find near-optimal solutions without falling into extremely long and unreasonable computational times.

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