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Constrained-Based Discrete-Event Simulation of an Assembly Job Shop Process in the Offshore Wind Industry

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Abstract

The problem of assembly job shop scheduling is presented in this paper by means of a manufacturing process of semi-submersible foundations in a constrained-based environment. We developed a 3D discrete event simulation model which considered from resources and spatial restrictions to real schedules and project dates. The model allowed us to implement several proposed dispatching rules in order to validate the current construction strategy. We also performed an optimisation of some parametrised dispatching rules in the search of better schedules, according to pre-defined measures of performance. We eventually found significant reductions concerning the blockages produced in the process, whose avoidance may limit risks and yield profits with a view to project overlapping. The model developed may also be applied to new scenarios of the present case, as well as to future projects with similar construction strategies.

Keywords: offshore wind, dispatching rules, assembly job shop, constrained-based simulation.

1. Introduction

One of the top priorities of every company when ameliorating internal processes is to find the right tools or approaches which allow facing day-to-day challenges in a more accessible and enriching fashion. However, when it comes to scheduling, firms generally do not look for optimal solutions, but for feasible and effective schedules, reminding that changes rapidly come up and new requirements may be established (König et al. 2007). Thus, dispatching rules arise as an accepted tool for real-time scheduling which may yield suitable and counter-intuitive solutions while remaining close to reality (Bard et al. 2015).

DES provide with the adequate means to implement them at the same time we can easily accommodate these new process requirements, consider machine failures and changeovers and introduce real schedule and resource constraints. In addition, the remarkable upgrade concerning 3D visuals strengthen the process of model validation and accelerates the comprehension of outcomes by non-expert personnel. As a whole, it brings closer the so-called concept of virtual factory applied to manufacturing.

On the account of the above, in this paper we present a case study from the offshore wind industry where a 3D DES model has been developed and several dispatching rules have been implemented and evaluated in accordance with some predefined measures of performance to validate the current construction strategy. The simulation model also allowed us to revise and propose new schedules which could improve the current construction strategy in terms of earliness and resource blockages. We also obtained a versatile ongoing model subject to be adapted without great difficulty to future projects that share the same manufacturing process.

Finally, this all takes place in the context of an industry in expansion whose role still remains uncertain due to a certain lack of competitiveness with respect to other renewable alternatives. Thus, considerable technology improvements and efficient supply chains will be essential for the success of the offshore wind energy.

2. State of the art

2.1. Offshore wind industry

Recently, offshore wind energy has recorded upwards trends both with regard to installed turbines capacity and grid-connected turbines (Ramirez et al., 2020). According to Poudineh et al. (2017), in the next 20 years, three quarters of new investments in power generation worldwide will be spent on wind and solar technologies. In this regard, offshore wind energy has the perfect opportunity to firmly position itself in the global generation mix.

Nevertheless, big goals have yet to be achieved for the offshore wind to become truly competitive with respect to its onshore cousin (Poudineh et al., 2017; GmbH, 2020). And this partly will hinge upon the extension of wind farms into high seas through the use of floating structures. With 57MW of capacity installed in 2018, floating foundations are expected to be the key to widening market opportunities by taking advantage of economies of scale. (Varela-Vázquez & Sánchez-Carreira, 2017; GmbH, 2020).

In the medium-term, semi-submersible foundations are expected to dominate the market accounting for almost all upcoming projects as shown in Figure 1. Given that they represent up to a 30% of the cost of the whole wind turbine (Lamas-Rodríguez et al., 2016), their competitiveness will have a significant bearing on offshore wind attractiveness.

In consequence, research into supply chain optimisation is needed in order for offshore wind to finally success while aligning itself with the technology upgrade entailed by the Industry 4.0. With this in mind, this study case proposes an innovative approach aimed at improving the way manufacturing setbacks are faced, as well as at allowing more competitive bidding and negotiations.

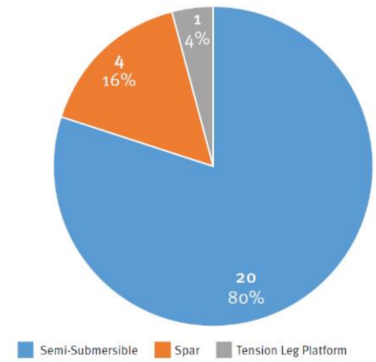

Figure 1. Number of projects by foundation design in the medium term (from Hannon et al. (2019)).

2.2. Discrete-event simulation and dispatching rules

Discrete-event simulation (DES) and dispatching rules have been gone hand in hand for a long time now, especially on the grounds that DES can easily handle stochastic activities and accommodate failures and changeovers in contrast to other approaches like mathematical modelling (Bard et al., 2015). This tandem has been widely used in the research field of scheduling with many and varied study cases. However, when it comes to assembly shops which are present in many manufacturing processes, these involve multi-level jobs that make the problem more complex in terms of modelling and problem-solving. Moreover, if we require higher modelling accuracy and detailed 3D representation as companies more and more demand, it becomes harder to find cases in the literature that fulfil all the requirements. In the next paragraphs, we put forward a brief summary of the main references found in the literature on assembly job shop scheduling and DES, although most of them focus on the study of rules and lack the multi-purpose service DES can supply.

Thiagarajan & Rajendran (2005) formulates the assembly job scheduling problem by considering relative costs of earliness, tardiness and holding of jobs as scalar weighs. They looked for the minimisation of the sum of weighted earliness, weighted tardiness and weighted flowtime of jobs. Among the rules they highlight as best performers, we can find an important role played by the TWKR (total work content of all operations remaining).

Natarajan et al. (2007) proposed new priority rules in assembly job shops aimed at minimising weighted flowtime and tardiness of jobs. Although the study is limited by constant processing times and absence of queue length restrictions, they found their proposed rules to outperform what they called the existing ones.

König et al. (2007) modelled outfitting tasks in shipbuilding and civil engineering with high level of detail by using DES as framework. They considered all the requirements of the process by differing its restrictions as hard and soft constraints, aiming at fulfilling as many as possible. They underline the appropriateness of simulation as a support tool in the planning process and point out the possibility of simulating different schedules and evaluating them with regard to utilization rates and costs incurred.

Lamas-Rodríguez et al. (2016) studied the problem of assembly job shop by means of a jackets manufacturing process. Through the study of different scenarios, they minimised flowtime per jacket, optimised workstations' utilization and balanced the fabrication line. They also highlight how DES can help companies increase their profitability without involving too much investment.

Jia et al. (2019) used a DES model together with a greedy randomised adaptive search procedure (GRASP) to statistically examine six dispatching rules in semiconductor assembly and test operations. They found that two of them performed better at minimising the weighted shortage of components. They also remark that simulation is adequate to evaluate the results and gain insight into system performance.

Finally, the literature review on DES and optimisation methods for assembly systems carried out by Prajapat & Tiwari (2017) shows significant current trends on the field. They noticed an increase in the use of hybrid methods in process simulation as well as in the application of artificial intelligence methods and multi-objective optimisation of simulation models. They also found what-if scenario analysis to be the most widespread approach.

3. Manufacturing Process of Semi-Submersible Foundations

Manufacturing process of semi-submersible foundations is considered as project manufacturing whereby every substructure (floater) is undertaken by means of fabrication workshops which produce relatively small units. Once fabricated, these components are assembled into sub-assemblies and, eventually, a final assembly operation brings these sub-parts together forming the floater. The process presents a high degree of prefabrication for most small components and a close-to-Lean methodology concerning the material procurement and manufacturing phases.

3.1. Parts of a floater

As shown in Figure 2, every foundation consists of three columns which are connected by tubular trusses (bracings) made up of diagonal and horizontal tubes linked by nodes. Besides, every column has a Water Entrapment Plate (WEP) at its bottom or keel, which provide motion control to the platform. Platform columns are sequentially numbered so that column 3 is the one on which the turbine tower will be installed. Due to this, its construction is more complex and longer in time with respect to columns 1 and 2, which are equal one another for our purposes.

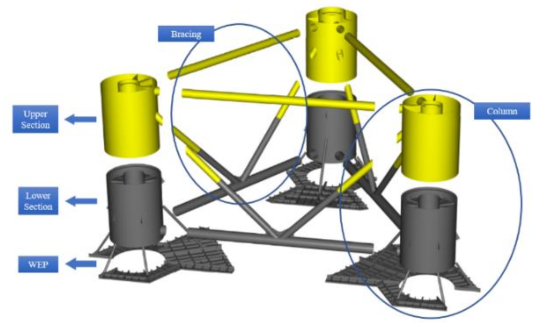

Figure 2. Main parts of a floater.

3.2. Construction strategy

The project consists in the assembly and delivery of five semi-submersible platforms numbered in ascending order from 1 to 5. Despite not completing Columns Assembly (AC) in the company's facilities, floater 3 was also considered because it affects Outfitting and Painting works. The construction strategy is shown in Figure 3.

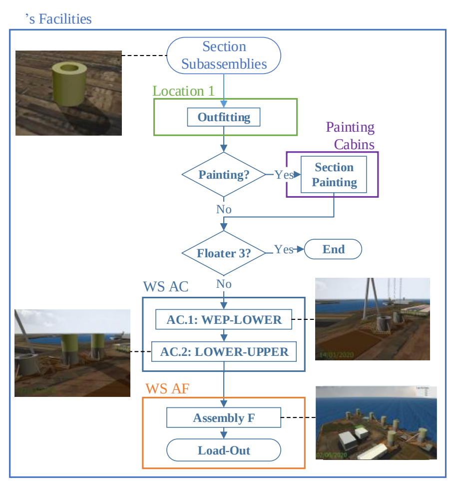

Figure 3. Process flow diagram.

Our study is focused on two stages: the assembly of lower and upper sections into columns (Column Assembly), and the final assembly of the floater (Floater Assembly or AF), where columns are put together and connected by bracings. We set the start point of the model flow at the entry of Outfitting.

AC can be carried out in several workstations (WS AC) although a set of spatial constraints affect critically input and output material movements. Figure 4 summarised these restrictions.

On the other hand, the project baseline contemplates specific assignments between AF workplaces and floaters, according to the number of the latter. These pre-defined assignments detailed in Figure 5 are also considered in the model.

Finally, delivery milestones are defined for every platform.

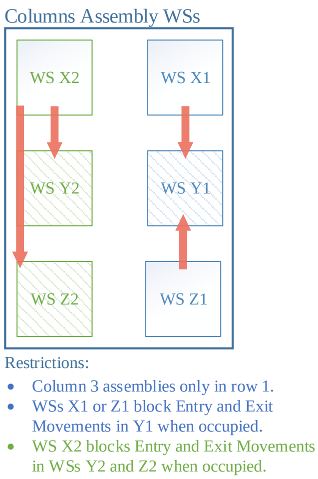

Figure 4. Restrictions on AC Workstations

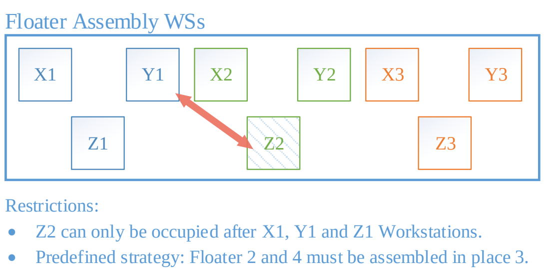

Figure 5. Restrictions on AF Workstations.

4. Methodology

4.1. Data collection

Personnel of Company provided us with a detailed description of the construction strategy and spatial constraints along with all MS Project files for every scenario. From them, we extracted subassemblies availability dates, task durations, floaters due dates and resource restrictions. These data were later input in FlexSim in the shape of tables and code to model the restrictions. The company also provided the 3D models of the flow items.

Regarding task times, these are deterministic and vary as to the type of section and column. Table 1 summarises them.

Table 1. Durations of process tasks considered.

Activity \ Section	C3-U (d)	C3 -L (d)	C1/C2 U (d)	C1/C2 L (d)
Outfitting	10	8	10	8
Painting	20	10	20	-
AC	12	25	12	20
AF	75	75	75	75
Load-Out	20	20	20	20

4.2. Problem statement

The problem addressed here applies to an assembly job shop scheduling with three levels within the product structure, from the sections to the columns and to the final floaters. There are 2 points in the process flow where it's necessary to decide a suitable sequence of items and a feasible assignment of resources.

Along with the above, the restrictions imposed by spatial requirements and available resources make the problem more complex, by adding constraints that diminish the search space. Therefore, it becomes harder to find valid solutions that meet the deadlines while fulfilling all the restrictions. We have considered these restrictions as hard constraints (König et al., 2007) so that they cannot be ever violated. The reason is the high cost of putting aside a column to free an AC workstation.

Finally, nowadays the project has been suffering from succeeding delays which affect the design plans of column 3 of all the platforms. We defined 3 scenarios:

- Scenario 1. Baseline Schedule where floaters manufacturing is sequential and balanced. Arrival dates of floater 1 subassemblies are earlier than floater 2 section's and so on.
- Scenario 2. Some delays affect the project as a whole and columns 3 specifically. Therefore, columns 3 AC due dates are rescheduled about 2 months later with respect to AC due dates of their corresponding columns 1 and 2.
- Scenario 3. The project undergoes very serious issues and all AC due dates are delayed around 1 month and a half. Columns 3 AC due dates are put off until 3 months later than AC due dates of their corresponding columns 1 and 2.

4.3. Discrete event simulation

Given the complexity of the case explained above, we considered Discrete Event Simulation as an adequate tool to carry out the study. In contrast to mathematical modelling, DES facilitates the inclusion of either spatial and resource constraints of the process and the creation of experiments to try different dispatching rules and check unknown scheduling strategies.

In our case, DES also provides the company with an ongoing model (see (Robinson, 2004) for nomenclature) that may be recycled for future projects with similar construction strategies.

Lastly, as for the selected software, we have chosen FlexSim for the personnel's experience with the software, the flexibility of the Process Flow tool and the powerful 3D graphics that enhances the validation phase and strengthens the comprehension of outcomes by non-expert personnel and managers.

4.4. Dispatching Rules

As far as the scheduling problem is concerned, we considered dispatching rules as a proper method to model the decision-making process since they keep the problem close to reality. As previously stated, the latter takes place in 2 stages of the process flow (AC and AF) and affects the priority between jobs and the assignment of resources (workstations and workplaces).

Every dispatching rule was tested in every scenario so that we could examine its robustness throughout the whole evolution of the project.

4.4.1. AC product assignment

In the case of AC, when it comes to decide the lower section to be scheduled, we first considered several basic rules in the initial and hence looser scenario: First-In-First-Out (FIFO), Shortest Due Date (SDD) and Critical Ratio (CR) with respect to A1 baseline due dates.

Then, we proposed the STR/COL rule based on product characteristics, that is, on the number of the structure (STR) as primary rule and the column number (COL) as a tie breaker.

We also put forward a revision of the CR rule, the Relative Critical Ratio (RCR) (1), which is based on the concept of TWKR (Natarajan et al., 2007) (Thiagarajan & Rajendran, 2005), customised to our case in (2) (The notation is taken from (Natarajan et al. 2007)). In contrast to the standard CR, the RCR takes into consideration the lower sections that are expected to arrive in a certain period R, as well as the remaining work time of their respective counter upper section, thus becoming a Global Job Status rule (Maxwell & Mehra, 1968). Therefore, RCR allows the model to reserve a berth for an upcoming section.

$$RCR_i = \frac{(D_i - CT) + TWRK_i}{C_i} \; if \; LTRW_i \leq R \qquad (1)$$

Where:

- RCR_i: Relative Critical Ratio of lower section *i* (the section with minimum RCR value is chosen)
- D_i: Load-out date of lower section *i* (due date).
- CT: Current time of simulation at which decision is to be made.
- C_i: Completion time of column *i* (AC total time).
- R: Constant that sets the maximum remaining work for lower sections to be considered in the decision.

$$TWRK_i = LTRW_i + UTRW_i \qquad (2)$$

Where:

- $LTRW_i$: Total Remaining Work of Lower section *i* in time units. It is equal the time of Outfitting plus Painting works (if applicable) if the section is yet to enter the process.
- $UTRW_i$: Total Remaining Work of Upper section *i* in time units. It is equal the time of Outfitting plus Painting works (if applicable) if the section is yet to enter the process.

The implementation of this rule into FlexSim involved serious issues as we needed to constantly track the current state of every item throughout the process in terms of TWKR without violating one of the paradigms of DES, that is efficiency. To do this, we developed a specific General Process Flow (Figure 6) based on triggers where tokens associated to items in process update a label with the current remaining time only when a decision has to be made. This code also considered stations' down time.

Base on the berth reservation concept brought in by the RCR, we implemented the CR* and SDD*, which extend the respective priority rule (CR and SDD) upstream by considering the lower sections that are supposed to come in no longer than R weeks.

Eventually, we devised a combination of the previous dispatching rules. (3) illustrates it, where the coefficients a, b, c, d and e permit establishing the different weights.

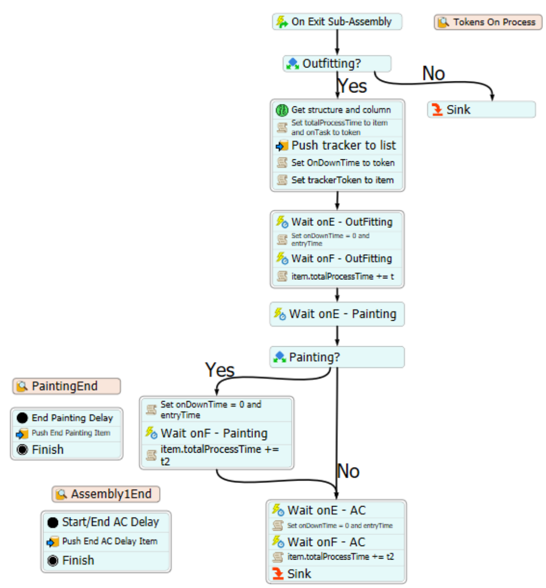

Figure 6. General Process Flow "Tracker" which tracks items state and works remaining time.

$$Z_i = aS_i + bCOL_i + cUA_i + dFIFO_i + eRCR_i \;\; if \; LTRW_i \leq R \qquad (3)$$

Where:

- Z_i: Priority index of lower section *i* (the section with maximum Z value is chosen).
- S_i: Structure to which lower section *i* belongs.
- UA_i: Respective Upper section Age since it entered the process. It's 0 if the upper has yet to start Outfitting works.

4.4.2. AC resources assignment

Regarding the AC workstations assignment, we can group the workstations according to their ranking starting from X1 to Z2, the row they belong (since C3 columns can only be assembled in row 1) and their susceptibility to be blocked. Thus, we implemented a dispatching rule based on these three features as represented in (4) where x, w and z are three coefficients with values that vary between -1 and 1 and which allow adjusting weights.

$$Z_j = x \times j + yRN_j + zB_j \qquad (4)$$

Where:

- Z_j: Priority index of WS j (the WS with maximum Z value is chosen).
- RN_j: Row Number of WS j (1 or 2).
- B_j: Boolean value that indicates if the berth j is subject to blockage.

Finally, we set workstation selection as prior to lower selection so that, if no suitable WS is found for the selected lower section i, next lower section i+1 in the list (if existing) is attempted to be scheduled. However, we also added the possibility of waiting for AC ongoing columns to be finished before a newly scheduled section takes up the adjacent workstation. In this way, the highest-indexed columns have always preference to abandon the workstation before being blocked.

4.4.3. AF assignments

Regarding the AF, we initially followed a FIFO strategy on the grounds of its assumed lack of impact in the scheduling performance. Afterwards, the imposition of preassigned locations for each platform remove the necessity of modelling it.

4.5. Measures of performance

The measures of performance are:

- Fulfilment of floaters delivery milestones (%). There is a final due date per floater which cannot be violated.
- Minimisation of total tardiness (days) with respect to floaters load-out dates. It must be 0 in order not to violate any milestone. However, its calculation provides with more information on the discussion of the dispatching rules used.
- Maximisation of total earliness (days) with respect to actual due dates.
- Minimisation of AC and AF blockages (%). Used to untie rules that provide the same earliness.

4.6. Objectives of the study

The primary objective of this study is the validation and optimisation of the construction strategy of the foundations in the different scenarios presented by the company by means of realistic dispatching rules and DES. The proposed schedules must meet project due dates and milestones while satisfying the existing hard constraints. This concretely involves:

- The development a complete 3D DES model of the construction strategy. The model must serve for both the present study and the future presentation of new strategies and results to non-expert users like company managers.
- Discussion and definition of likely suitable dispatching rules according to the scenario in question.
- Validation and optimisation, if possible, of the current strategy of every scenario by means of the proposed dispatching rules.

4.7. Model verification and validation

The verification and validation of the model was performed in two steps: first, once developed and with the supervision of company's personnel, we thoroughly examined the behaviour of the model through visual checks, the creation of extreme conditions and the exhaustive revision of the code created in the Process Flow tool.

Then, we validated the solutions performed in every scenario by examining the outcomes and the compliance of every restriction. Besides, the perfect alignment of the SDD* rule in scenario 1 with the actual schedule allowed us to validate the model and the real strategy simultaneously. In scenarios 2 and 3 where no modifications beyond availability dates were considered, the robustness of the results obtained eventually reinforced the validation phase.

4.8. Optimisation of parametrised dispatching rules

When it comes to parametrised rules such as CR* or SDD*, we made use of the optimiser OptQuest provided in FlexSim. This optimiser was sufficient for our purposes and no excessively long calculation times were encountered. We established coefficients as discrete with variation intervals between 2 and -2, and from 0 to 30 for R. We consider these values as reasonable with a view to limiting the search space. The discretization could also keep the decision-making close to reality, by identifying which rules prevails the most. After setting the minimisation of total tardiness and maximisation of total earliness as objectives, we extracted the best solution in terms of the performance measures abovementioned.

5. Results and Discussion

Table 2 summarises the results obtained in scenario 1 for the different dispatching rules. Every record of the table corresponds to the best result of the priority rule in the scenario. Table 3 shows blockages for all the scenarios considered.

Table 2. Results of scenario 1.

Dispatching Rule	Tardiness (weeks)	Earliness (weeks)	Fulfilled Milestones (%)
FIFO	0	3,0	100%
SDD	0,5	4,8	80%
SDD*	0	0	100%
CR	0,5	5,5	80%
CR*	0	0	100%
STR/COL	0	3,0	100%
RCR	0	3,0	100%
(3)	0	4,0	100%

In this first case, the absence of significant tightness in the schedule caused the majority of the rules to fulfil all the milestones and even record more optimal solutions. A FIFO approach was enough to obtain an improved strategy with respect to real dates, despite not taking care of possible blockages. However, results already indicated that, although they yielded positive earliness, basic rules like CR and SDD were not valid for this case, and that we needed to extend the decision making upstream in order to consider higher priority lower sections which are yet to arrive.

On the other hand, SDD* let us validate the current strategy since it was perfectly aligned with the real schedule. CR* provided unclear results because, despite their good performance in terms of blockages reduction, they did not improve the actual strategy. Our proposed rules RCR and STR/COL did not seem to stand out from the rest. Nevertheless, the (3) provided the best of the solutions with an 15% of blockages reduction in AC and AF while fulfilling all the milestones.

Table 3. AC and AF blockages reduction in all the scenarios.

Blockages Reduction	Scenario 1	Scenario 2	Scenario 3
FIFO	0%	0%	0%
SDD*	0%	-11%	0%
CR*	2%	0%	5%
STR/COL	0%	7%	0%
RCR	0%	0%	5%
(3)	15%	24%	43%

Results from scenario 2 (Table 3 and Table 4) confirmed some of the notions prompted in scenario 1 with regard to simple SDD or CR which did not suit the present study. Like them, basic rules like FIFO were no longer valid. All rules yielded a certain earliness with very close values among them. This earliness was mostly due to the optimisation of the strategy of floater 3, which does not complete AC and AF at the shipyard. That also meant that the construction strategy was already very restricted regarding the rest of floaters.

Table 4. Results of scenario 2.

Dispatching Rule	**Tardiness (weeks)**	**Earliness (weeks)**	**Fulfilled Milestones (%)**
FIFO	2,7	2,5	80%
SDD	2,7	2,5	80%
SDD*	2,7	2,5	80%
CR	2,7	2,5	80%
CR*	2,7	2,5	80%
STR/COL	0	2,3	100%
RCR	2,7	2,5	80%
(3)	0	2,8	100%

As illustrated in the above table, only 2 priority rules seemed to succeed: STR/COL and (3). Both led to the abovementioned earliness of 10 days on the construction and a reduction of up to a 6% while fulfilling all the predefined milestones.

Finally, results from scenario 3 (Table 5 and Table 3) indicated a considerably improvement provided by (3) with respect to the rest of rules, with a reduction of 43% in blockages. Again, the earliness was mostly caused by floater 3 construction strategy. This scenario clearly confirmed that, in tighter schedules, only rules that permit workstation reservation like SDD* or CR* performed appropriately.

Table 5. Results of scenario 3.

Dispatching Rule	Tardiness (weeks)	Tardiness (weeks)	Fulfilled Milestones (%)
FIFO	4,4	1,6	80%
SDD	4,4	1,6	80%
SDD*	0	1,6	100%
CR	4,4	1,6	80%
CR*	0	1,6	100%
STR/COL	0	1,6	100%
RCR	4,4	1,6	80%
Equation 3	0	1,6	100%

It is worth noting how the STR/COL rule based on the product characteristics turned out to be one of the best performers. Although it is closely related to the SDD due to the number-base labelling of floaters, it allowed more room for variations by using the column index as the tie breaker. On the contrary, the proposed rule RCR yielded no relevant insight on the process optimisation, so it should be discarded in future works.

The reduction in assembly blockages is also illustrated in Figure 7 and Figure 8 where the blockages produced both with the FIFO and (3) rules are coloured in red. It makes it clear how the dispatching rule adjusts the starts and ends of operations depending on the priority rule. The Gantt charts also show the blockage produced in workstation Z2 due to the existing restriction.

Table 6 shows the values of the coefficients of the best results provided by (3) in every scenario. Interestingly, the increase in R may indicate that, as the scenario becomes tighter it is necessary to look further back into the process so that we can reserve a workstation for columns which are still starting Outfitting.

Regarding the rest of coefficients, there are no similarities between scenarios which could denote either a significant dominance or negligibly of any rule.

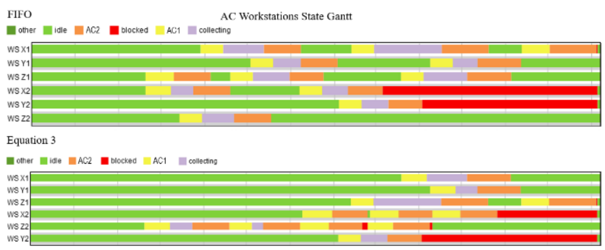

Figure 7. Gantt charts of AC with FIFO (above) and (3) (below) dispatching rules in scenario 3.

Figure 8. Gantt charts of AF with FIFO (above) and (3) (below) dispatching rules in scenario 3.

Table 6. Values of (3) coefficients from the best results in every scenario.

Weights/ Scenarios	1	2	3
a (STR)	-1	2	2
b (COL)	2	-2	-1
c (UA)	0	2	2
d (FIFO)	1	-1	-2
e (RCR)	1	-2	-2
R (Weeks)	16	29	30

The same is the case of the weights of the dispatching rule used for AC workstations assignment. Values for (3) best results are provided in Table 7, as a sample of the no dominance of one strategy. We considered the proposed dispatching rule as sufficiently flexible for our case, because it considers all the differences existing among workstations. However, every optimisation provided with different coefficients so no conclusions can be drawn.

Table 7. Values of AC workstations rule weights per scenario in the best case with (3).

Weights \Scenario	1	2	3
x	0	1	0
y	-1	-1	-1
z	-1	1	-1

With respect to the optimisation of coefficients, Figure 9 draws a comparison between the results for different dispatching rules in scenario 3 with minimisation of tardiness as primary objective. Given the amount of all possible combinations in every case, we considered times no longer than 20 minutes and, as expected, it was harder in the (3) case to yield pseudo-optimal results. We took this approach since we adopted the company's view, who looked for a compromise between optimisation time and accuracy of results. Besides, the quality of results obtained also showed that this approach was valid for the present case.

Lastly, Figure 10 shows a screenshot of the 3D model during the runtime of scenario 3.

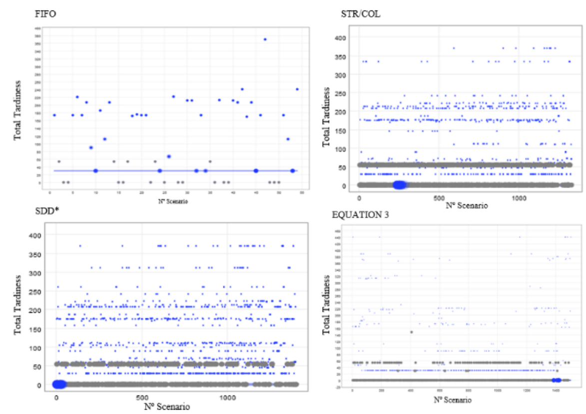

Figure 9. OptQuest results in scenario 3 for FIFO, STR/COL, SDD* and (3) rules

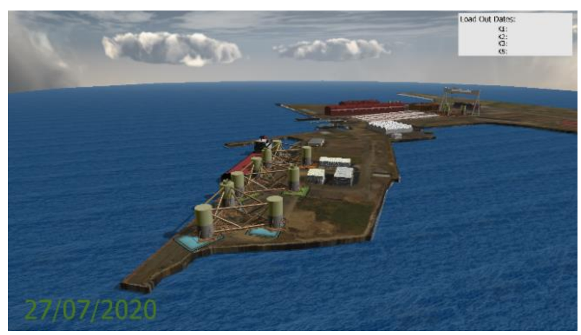

Figure 10. Screenshot of the final 3D DES model.

6. Conclusions and Future Work

The use of discrete-event simulation and dispatching rules in the validation and optimisation of the construction strategy of five semi-submersible foundations is presented in this paper. The problem addressed here applies to assembly job shop scheduling in a constrained-based process.

First, we developed a 3D DES model which contemplated all the necessary spatial and resources restrictions involved in the real process. We also added components availability dates, task times and project due dates which were provided by the company. Afterwards, we defined the dispatching rules to be tested, along with the measures of performance. Once the rules were implemented and the model validated, we optimised the parametrised rules and extracted results in every scenario. Finally, we evaluated their performance and drew a comparison to find out the most suitable ones. We also obtained an ongoing 3D DES model subject to adaptation to future projects with similar construction strategies.

The multi-job shop problem faced in this case study has allowed us to gain some insight regarding both the process and the methodology.

With respect to the first, we obtained more optimal construction strategies with major improvements regarding the blockages produced in the different assemblies. By better taking advantage of the available resources, we could avoid possible risks or even overlap different projects which, in turn, could yield significant profits to the company.

On the other hand, we confirmed the validity of DES either as a decision-making and project scheduling tool. The possibility of easily and accurately modelling real schedules and breakdowns as well as obtaining precise forecasts proves the remarkable versality of this tool. This is successfully completed with the 3D environment, which dramatically accelerates and ameliorates the validation process as well as the comprehension of their results by non-expert users.

Lastly, it is also worth noting the limits of the present case, that is, that task times are deterministic, and the rules are set once for all at the beginning of the process. Therefore, future studies could consider some degree of variability in job times, for what DES suits perfectly. We also propose the possibility of studying the dynamic use of dispatching rules, where the primary rule could be reconsidered and changed once in a while according to predefined time intervals. Although it considerably enlarges the search space, it may also provide more suitable solutions without the need for applying case-specific adjustments like we did here. For this future work, a larger process in terms of product units should be also considered.

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