COMPUTERS AND INFORMATICS
2757-8259 2021, Volume 1 Issue 1
Research Article

Discrete event simulation and ergonomic software for the design of a visual testing system in an automatized workshop of jacket nodes

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Submitted: 15.10.2020
Accepted: 25.11.2020
Published: 28.02.2021

Abstract:

Offshore wind power is poised to make a major difference to decarbonizing the energy sector yet still faces a certain degree of uncertainty with respect to its eventual cost competitiveness. In the case of jacket foundations, the leap from manual to robotized node welding may lead to a reduction of 30% in terms of manufacturing costs. For this reason, in this paper we present a case study where we have used the 3D discrete event simulator FlexSim along with the ergonomic package Tecnomatix Jack to design and optimize the implementation of a new visual test system for jacket nodes. This system will be integrated by NAVANTIA to a future workshop which is a fundamental investment in its medium-term roadmap. To this end, after the definition and creation of several scenarios in FlexSim to analyze the new production system, we developed detailed 3D animations of the worker performance. These animations raised the need for a more detailed ergonomic study. Hence, we then performed RULA analyses of the task with Tecnomatix Jack and proposed more ergonomic alternatives out of them. Finally, we adopted these changes into new 3D animation in FlexSim and obtained a final integrated model.

***Keywords**: Discrete event simulation, Ergonomic analysis, Industry 4.0, Jackets nodes welding, Offshore wind*

Nomenclature	
DES	Discrete Event Simulation
RULA	Rapid Upper Limb Assessment
JLB	Jacket Lower Block
JUB	Jacket Upper Block
TP	Transition Piece
NDT	Non-Destructive Test
DC	Dimensional Control
VT	Visual Testing
ERP	Enterprise Resource Planning
PED	Production and Engineering Division
JaCo	Improved Fatigue Life of Welded Jacket Connections

Cite this paper as: Rodríguez A. L., Álvarez J. P., & López I. T., Discrete event simulation and ergonomic software for the design of a visual testing system in an automatized workshop of jacket nodes, *Computers and Informatics*, 2021, *1*(1), 12-25.

1. INTRODUCTION

Amid an increasing global demand of energy and the high priority need for renewable and competitive energy sources, offshore wind holds very high expectations in terms of scheduled investments in the medium and long-term. Its onshore cousin is becoming more and more restricted by several issues such as land availability and visual impacts that do not affect offshore wind and, hence, the companies have started to turn their attention to it [1-2]. Consequently, the offshore wind market has been recording upwards trends as to the capacity of the installed turbines and the size of the offshore farms and it counts already with 150 new projects planned over the next 5 years [3]. For all this together with the growing awareness of states on the harmful impacts of climate change, offshore wind energy is set to be the key to decarbonizing the power sector and driving energy transitions.

In the middle of this global transition, Europe deserves a special mention as to be leading the global offshore wind market recording the 80% of global installed offshore capacity wind capacity in 2018 [4]. EU considers the offshore wind sector as strategic within the wind industry, which already can meet 10.4% of the EU's electricity demand. In 2019, 7 wind farms were fully grid-connected whereas other 3 ended up partial-grid-connected, in the race for the ambitious target of 130GW that has set to be achieved by 2040 [5]. That also means that the European Union aims to fulfill the 40% of the global offshore market by 2040. However, behind this optimistic forecast underlies a certain degree of uncertainty. It still not very clear whether the offshore production will be attractive enough in terms of cost competitiveness to live up to these predictions. Offshore production involves remarkable foundation and installation costs, as well as additional expenses derived from operational and maintenance activities [6]. This leads to upfront capital costs much higher than other renewable alternatives such as solar energy or onshore wind. Therefore, the offshore industry claims for efficient supply chains and technology improvements which, in turn, bring in new opportunities for companies and research institutes to enhance the diffusion of this renewable energy and simultaneously shape the future.

One of these opportunities may lie in the robotization of jacket nodes welding. When planning the construction of a new offshore wind farm, jacket foundations turn to be a 15% of total capital expenditures [7], which is quite a significant percentage. However, as stated in [8], the robotization of the welding of jacket nodes may lead to a 60% reduction in manufacturing time of nodes, and subsequently a 30% decrease in jacket total costs. This is mainly because nodes are a cost driver within the manufacturing of jackets, and therefore, the right performance of their production becomes vital for that of the whole process

In parallel to all this, we are witnessing a technological revolution in the way we produce and deliver products and services. As mentioned in [9], the fusion of the activities of design, industry and society generates the change in management and analysis of the production process through the implementation of advanced technologies for Industry 4.0. Likewise, we make use of new concepts such us Smart Manufacturing to try to enclose all the different aspects brought up by this revolution that affect the manufacturing processes, from Automatization to Cloud Computing and to IIoT [10]. Among them we can locate the Digital Manufacturing (DM), which entails a new more effective way of producing things. In brief, as global markets demand more flexibility, customization and shorter production times, DM allows us to become more and more cost competitive by continuously analyzing the way we fabricate [11]. It also will contribute to boosting costumer's confidence at the same time we improve the wellness of our employees. Therefore, we identify it as part of the solution to the necessities posed by offshore wind.

Hence, here we present a case study where we have used 3D discrete-event simulation (DES) coupled with a human simulation package to design and optimize the implementation of a new system for Visual Testing (VT) of jacket's nodes in a future workshop for robotized welding of nodes. This workshop will be set up by the international renowned Spanish shipbuilder NAVANTIA S.A, and the new VT system is based on a node's rotator and non-contact inspection system.

Our purpose is to present an innovative approach that allows optimizing a manufacturing process by adopting a human-centered perspective. We believe offshore wind must face its goals by considering all different perspectives involved in the process, and thus we highlight here the importance of the wellness of the worker. Therefore, not only have we optimized the system in terms of productivity and cost, but also analyzed it from an ergonomic viewpoint.

To accomplish this, we have first applied DES. This simulation paradigm let us study beforehand the aggregated effect of a change or a new implementation in a production system. This also leads to cost-savings since we do not have to commit any resource in the process. However, this is of special importance when the system presents high variability, so we cannot foresee how it will behave in a concrete what-if scenario. A literature review shows that cases that addresses the logistical problems in the production in offshore wind are not abundant [12]. In general, risks and uncertainties are considered by means of safety margins and historical data. This leads to higher manufacturing costs that affect the feasibility of new offshore wind farms.

However, there are still come good examples that evidence the significant outcomes that DES can provide. One of them can be found in [13] where several DES models were developed with the aim of reducing flowtime per jacket and minimizing the probability of missing due dates. To this end, through DES they identified process bottlenecks and performed adjustment of manufacturing times to agreed-upon due dates.

In the case of [14], a 3D discrete-event simulation is used to study and asses the internal logistics of a shipyard with regard to costs and resources involved in transportation activities of jackets, load-out operations included. The tool also allowed the calculation of entry and exit dates of each buffer in every storage space considered.

[15] draws a parallel between shipbuilding primary manufacturing workshops and the ones from offshore wind. In both cases they face agreed-upon milestones whose non-compliance usually result in severe economic penalties. By applying DES to the management of shipyard resources engaged in a jackets manufacturing process, different strategies for resource allocation are examined.

We must also mention the recent improvements in 3D graphics applied to DES, especially in commercial software, most of them derived from the videogame industry. The inclusion of high-quality 3D graphics has transformed the old DES paradigm into a renewed powerful tool that may even function as a marketing ploy. In fact, the high fidelity of the 3D world and the inclusion of 3D animations into the DES model has been part of the key to the present study, since it allowed us the build bridges between both software employed here. This new perspective puts forward the concept of a future all-in-one tool which may automatically establish connections between different kind of analyses, so that we can study a new implementation from all points of view without the need of modelling things more than once.

On the other hand, conventional risk assessment of physical work methods is time-consuming and requires human subjects to perform the operational task, whereas 3D visualization allows users to simulate the process and reduce the time and the need for costly onsite devices, as exposed in [16]. Therefore, to adopt the human-centered perspective, we have used Tecnomatix JACK from Siemens PLM, an ergonomics simulation package to carry out detailed simulations on the kind efforts that workers must withstand when doing a concrete operation. As [17] and [18] say, Tecnomatix jack offers the possibility of organizing the workplace both ergonomically and logistically, helping to define the factors that affect job performance in virtual reality. In this sense, what is most common nowadays is to perform post-analyses, that is, to study an already existing process that is believed to cause any kind of ergonomic issue, as stated in [19]. However, as they also do, we here propose an alternative methodology purely based on preventive virtual simulations. In other words, we take actions in the early design phase to prevent future issues from arising once the new operation in question is already set up [20].

For the ergonomic analysis we have selected the RULA, Rapid Upper Limb Assessment, as they have done in work [21] and [22]. The main reason why we have decided to apply RULA is because, as revealed by study [23], it is a method that can be applied to workers in any field and its use has been increasing over the last 10 years, indicating it is an effective method which is being used more and more. This analysis divides the body into two parts that form two groups, group A, which includes the forearm and upper arm and wrist, and group B, which consist of body, neck, and legs, as explained in [24]. Through the tables associated with the method, a score is assigned to each body area and then global values are assigned to each of the groups and finally the final score is obtained from them.

All in all, DES and Virtual Ergonomics come to be two basic pillars of Digital Simulation, which is in turn an essential part of Digital Manufacturing. In this way, we have applied and connected these two smart technologies between one another to study and design a new step in a system that still does not exist in the present, but which probably will signify a step up and onwards for NAVANTIA competitiveness, as well as for the future of offshore wind.

2. CASE DESCRIPTION

The fifth largest shipbuilder in Europe NAVANTIA S.A. has been diversifying its production during the last decade by undertaking construction projects of offshore wind foundations. Therefore, as a part of its present strategy, it has considered the creation of a new workshop for robotized nodes' welding to be profitable and of great importance for its medium-term roadmap.

One very important advantage over its competitors is the availability of a welding robot developed in a previous R&D project called JaCo (Improved fatigue life of welded jacket connections), which is full operational and could be further adapted to various typologies of nodes. This robot makes up the main investment and thus obstacle for other companies before switching from manual to robotized welding. Since NAVANTIA already counts with it, it is now fully committed to the creation of the complete workshop with the final target of reducing the cost of producing jackets, a type of offshore substructure NAVANTIA has bet on. NAVANTIA aims to optimize the design of the jacket foundations through improved fatigue standards and the validation of both faster welding tests and manufacturing methods: that is, robotized welding.

So far, NAVANTIA has subcontracted the production of nodes to local companies and hence have not direct access to either disaggregated production costs or process' stages cycle times. In this sense, before taking on the investment and out of the concern of the presented paper, we have developed a 3D DES model of the future workshop based on the current available data in order to size the stations, buffers and personnel needed in it. This workshop must comply with the current flow time of the shipyard, that is, it must produce all the nodes of a jacket per week. In the design of this new workshop through DES, we have identified a bottleneck in the Visual Testing operation of nodes, which demands a high number of resources and personnel to ensure the cited flow rate. Therefore, our objective will be to propose a new solution for this station in accordance with NAVANTIA requirements:

- The new VT system must be based on cutting-edge technology able to be connected and synchronized with the digital twin of the workshop.
- It must fulfill the current flow rate of the factory: 1 jacket per week.

- It must be integrated in the existing 3D DES model that will configure the digital twin of the factory. Thus, this model is set up as a Regular Use Model, which requires a high level of accuracy and a continuous alignment of the model with the real system [25].

The new solution must also optimize human well-being and overall system performance.

2.1. Jacket's Nodes

Jackets are can be coarsely divided, as showed in **Error! Reference source not found.**, into the following four parts:

- The stabbings
- The Jacket Lower Block (JLB)
- Jacket Upper Block (JUB)
- The Transition Piece (TP), between the jacket body and the wind turbine tower.

The JUB and JLB are in turn made up of braces and legs which, for their part, consist of tubular elements connected by transition nodes, namely, jacket's nodes. These latter are steel tubular steel joints made up of at least two stubs and a central chord. It is important to note that the jackets present three different types of nodes depending on their role and shape: Y, X and K-shaped nodes, although in principle the manufacture of K nodes have been discarded in the design of the workshop since they are currently unmanageable by the robot.

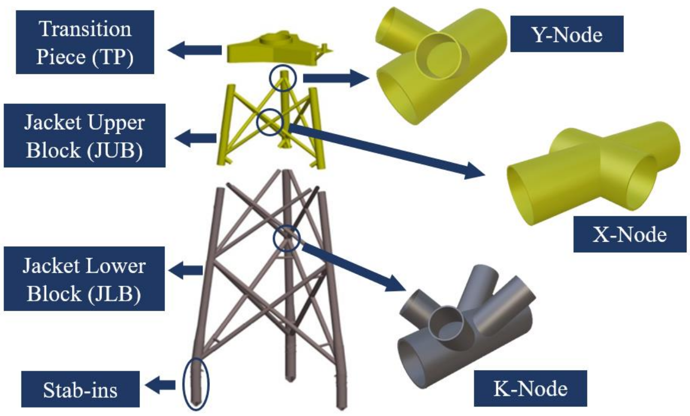

Figure 1. Main components of a jacket.

We must also note that the dimensions and characteristics of every node may vary according to the design of the jacket at issue and its position within it. This means that two X nodes may share morphology parameters, but they will be different to one another as to the bay which they belong to, that is, their position along the structure height. We may even have a unique project which includes several clusters of jackets depending on the depth the latter will be located on. In this case, the characteristics of the X and Y nodes are likely to vary considerably depending on the cluster which they belong to. Thus, it is of vital importance to design the new VT system in a way that has to be suitable for most general node's typologies, as well as easily convertible to new designs without the need to commit extra resources.

2.2. Manual Welding and Visual Testing

Before digging into the robotized welding, regarding the manual welding we can coarsely differentiate three phases sequentially performed: the root pass; the rest of filling and capping passes; and the subsequent Non-Destructive Test (NDT) and Dimensional Control (DC) processes.

In relation to these tasks, we must take notice of two points which give us a glimpse of the current hurdles manual welding presents:

- During the welding passes, there is limited accessibility for the welders from the inside of the node. Along with these, the preheating temperature of stubs make the operation conditions particularly difficult and thus require welders to have high manual skills.
- NDT process is composed of several phases, one of which is Visual Testing (VT). Once the inspector has carried out the VT, he fulfills the form template and then he submits it into the project database. This two-sequential-step procedure takes several hours to have the data available within the enterprise resource planning (ERP) software. However, since the manual welding is a slow process, there has not been so far need for inspection time reduction.

2.3. Robotised Welding and automated NDT

The welding robot has already demonstrated its validity to solve the first difficulty, as no welder is needed anymore for the filling and capping passes, that take most of the welding time. Along with this, the robotized welding increases the deposition rate up to 7 times the manual one while reducing the defect rate and avoiding reworks. This transfers the bottleneck to the NDT phase so that a new VT system is urgently needed.

Thus, when it comes to automation of NDT, here we propose a system based on two main components:

- a node's adjustable rotator able to adapt itself to the different kind of nodes and rotate the node up to the selected position by the inspector (Figure 1);
- and a portable, non-contact weld and joint inspection system for VT (**Error! Reference source not found.Error! Reference source not found.**) that can transfer the data directly to the ERP removing the need for manually fulfilling any template.

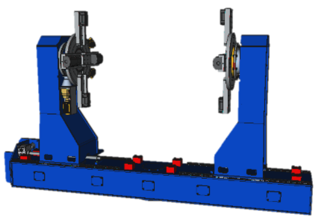

Figure 1. Node's adjustable rotator.

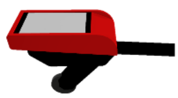

Figure 2. Non-contact weld and joint inspection system.

The rotor has been designed to allow the movement of the node in a simple and fast way, thus avoiding having to use the bridge crane every time the inspectors need to access another area of the node. In turn, the portable inspection system greatly simplifies the task and automatically records the results, which previously lasted several days since the operator had to have hours in which there is no inspection to complete the reports.

In summary, although the new system is not completely robotized and must be executed by an operator, but we can highlight at least four important advantages over the traditional method:

- Quicker inspection as the system automatically interprets the information on the welded being inspected.
- The new non-contact inspection system holds Wi-Fi connection through which automatically records information into the company's ERP system.
- No need for external means like overhead cranes to reposition the node during the process which in turn shortens the task duration even more.
- Significant ergonomic improvement.

3. METHODOLOGY

3.1. Data Collection

Our main data sources for this paper have been twofold:

- NAVANTIA has provided us with information from previous projects on jackets manufacturing carried out by the company in the shape of MS Project files. We have break down this information to compare current task times with the new system's expected ones.
- The personnel of the Production and Engineering Division (PED) have also collaborated in the selection of the technology, the definition of task times ranges, as well as in the development and validation of models.

3.2. Discrete-Event Simulation Models

Regarding the simulation of the Visual Testing system from a productivity point of view, the case presents three main features that make 3D DES very suitable for the study. On the on hand, there is a certain degree of uncertainty presented both in the task durations, as well as on the system to implement. This leads to the need for a very versatile tool that allows us to continuously modify a model without having to reprogram or modify the system up or downstream. Besides, there is the need imposed partly by NAVANTIA of a 3D representation of the model, so that it can serve also to explain the changes in the system to non-expert personnel and to the customer. Furthermore, the tool must offer the possibility of modelling detailed 3D animations of the worker in order to examine the need for further ergonomic analysis. Finally, the tool has to allow connection with the real system concerning NAVANTIA's future objective of achieving a integrated digital twin. In this sense, we have selected the commercial DES software FlexSim, which fulfills all the requirements and which we had previous experience on.

With regard to the methodology, we first integrated the current layout of the predefined company facility for the workshop in FlexSim, including the CAD plane and existing resources such as overhead travelling cranes and carts. Afterwards, we modeled the different stages that will make up the workshop: stubs cutting and beveling, DC phases, root pass beads, JaCo robot and final NDT. The duration of every task was estimated based on historical data and under the supervision of NAVANTIA's personnel. In order to consider the variability, most task times have been adjusted to uniforms distributions. In the case of NDT, we first include the manual inspection to examine the amount of resources (stations and workers) needed.

Afterwards, we sized every station involved according to the shipyard flow time of 1 jacket per week. Once we developed and validated the first model of the workshop, we changed the manual inspection system by including the node's adjustable rotator and the consequential new task times. Here is where FlexSim's animations module allowed us to develop realist animations of every operation and incorporate VT changes with a high degree of accuracy. We developed different animations according to the type of node and also studied the rotation of every node by the new system. It must be noted that every step was examined with Navantia experts, which also provided us with new cycle times distributions, reductions in defect rates respect to manual welding and accurate information on the position and movements of the worker. The high-quality 3D graphics provided by FlexSim allowed us to generate a synergy with NAVANTIA's personnel so that they continuously participated in the validation phase of the model and the animations.

Finally, after the completion of the ergonomic analysis, we modified the previous model to include the new positions of the worker which have proved to be much more ergonomic than the initial ones.

3.3. Tecnomatix Jack Models

As for the ergonomic analysis, we proposed the use of Tecnomatix JACK software to undertake the study. The choice was mostly based on its extended use in the literature review which acknowledge its intuitive interface usability. Tecnomatix Jack is Siemens human simulation and ergonomic analysis software used globally to build safe, efficient and more ergonomic workplaces. Allowing simulations, analysis and optimization of human operations.

We centered the study on the evaluation of postural load, one of the risk factors most commonly associated with the appearance of musculoskeletal-type disorders, and ways to reduce it. As evaluating method, we chose RULA (Rapid Upper Limb Assessment) method, one of the most widespread. This method assigns a score to each body area to obtain a final value, which is proportional to the risk involved in performing the task. RULA organizes the final scores into performance levels that guide the evaluator on the decisions to be made after the analysis. The proposed levels of action, see Table 1, go from level 1, which considers that the evaluated position is acceptable, to level 4, which indicates the urgent need for changes in the activity.

Table 1. RULA score, risk level and actions.

Score	Risk level	Action
<2	Acceptable	We must ensure that the situation is maintained over time.
3 or 4	Low	It is preferable to plan improvement actions to prevent certain risks.
5 or 6	High	Improvement actions are needed in a short time.
>7	Very high	It is necessary to involve as quickly as possible the doctor of the work or an ergonomist. If necessary, stop the operation of this workstation.

Once we set up the 3D scenario which was equal to VT station previously implemented in FlexSim, we evaluated the VT of both X- and Y-nodes and divided the movement into 2 postures.

4. RESULTS AND DISCUSION

In Fig. 4 we show the process flow of the new robotized welding workshop over the proposed 3D layout of the FlexSim model. This layout was configured by considering the different capacities of the overhead cranes, as well as the physical entries and exits of the real location of the workshop. Moreover, the figure shows the final design of the workshop, once we performed an optimization of the number of workstations and workers so that they satisfy the required flow time by manufacturing all X and Y nodes of one jacket per week.

The last steps of the process flow are the robotized welding station and the final NDT and DC. As can be seen in the layout, in the case of NDT, a specific zone was sized without specifying the concrete number of stations. For the purpose of our paper, this design corresponds to a baseline scenario in which traditional procedures are performed for NDT, within which VT is included. Along with this initial lack of definition, there is also uncertainty regarding the cycle time of the task, which was modeled through an exponential distribution with 7 hours as location and 4 as scale.

The developed model was fully parametrized so that we could undertake sensitivity analyses on any kind of resource included in the model, from stations to defect rates and machine cycle times. Therefore, once the global layout was set up, we performed the detailed analysis of NDT stations. Table 2 summarizes the 5 scenarios contemplated during the study:

- First, we kept the NDT and VT traditional procedures and studied the number of stations needed to fulfill the required flow time with such system. In scenario 1 with 2 stations included, we obtained a flow time of 9.54 days in order to produce all the nodes of one jacket. In scenario 2 we added an extra slot. However, in neither of them the target flow rate was reached.
- In scenario 3 we considered 4 NDT stations. In this case, it ensured a flow time of 7 days/jacket. Although this scenario is not feasible as we do not have such room in the span to include more than 3 NDT stations, it let us have an idea of the minimum resources needed to fulfill the required production rate.
- Scenario 4 comes to be the first that includes the new system based on a node's rotator along with the new VT system. In this case, the new cycle times were modelled as a triangular distribution a mean of 6h from a low bound of 4h up to an upper of 8h (these values were also validated by PED, who also foresaw a reduction in the variability of the process). The results show that this alternative does not reach the requested flow time. Furthermore, with just one NDT station, there would be the need for a system adjustable to both for X- and Y-nodes, which would make it much more expensive.
- Scenario 5 comes to be the final approach based on 2 node's rotators, one per type of node. This approach solves 3 questions simultaneously: it ensures the required flow time with certain floating time; it is less expensive than designing a multi-node rotator; and it fulfills the spatial requirements.

Table 2. Summary of DES scenarios and flow rates.

Scenario	Description	NDT Slots	NDT avg. cycle time (h/node)	Weeks/1 Jacket's nodes
1	Traditional method. 1 station per type of node.	2	9	0.73
2	Traditional method. 2 stations for X-Nodes, 1 for Y-nodes	3	9	0.96
3	Traditional method. 2 stations per type of node.	4	9	1.01
4	1 rotator and new inspection system	1	6	0.89
5	1 rotator per node type and new inspection system	2	6	1.02

Therefore, we selected Scenario 5 since it has the most suitable approach in the design of the VT stage. Afterwards, we developed detailed 3D animations of the operator performing the task in this scenario, as show in Fig. 5. This animation was also reviewed and validated by NAVANTIA's PED, so that it was virtually like the real one. Here we identified the need for performing an ergonomic analysis of the task since the animation put forward a poor posture of the operator and great difficulty when accessing certain parts of the node.

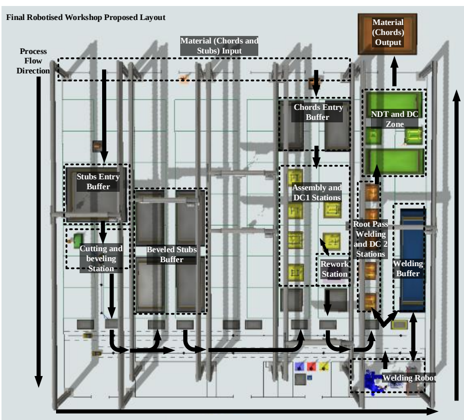

Figure 3. Node's adjustable rotator.

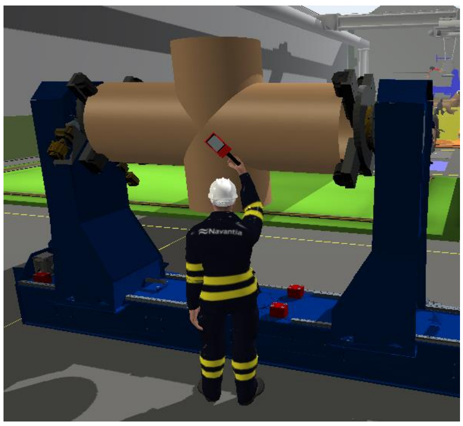

Figure 4. Non-contact weld and joint inspection system.

4.1. Ergonomic Analysis

Regarding the ergonomic analysis, once we implemented the 3D models of the node rotator and the portable inspection system in Tecnomatix Jack, we first studied several scenarios in the case of X-nodes:

- Scenario 1: The most unfavorable scenario in which the operator performs the inspection from the ground with predefined node's rotations during the VT.
- Scenario 2: An intermediate scenario in which we incorporated a platform to raise the operator and kept the standard rotation scheme.
- Scenario 3: The most ergonomic scenario. It includes the platform and we also improved the rotation scheme with more precise and ergonomic rotations from the perspective of facilitating operator's access.

The RULA scores obtained for each scenario are summarized in Table 3:

Table 3. Summary of results obtained in ergonomic analysis of node X.

N Scenario	Description	Score RULA Posture 1-Node X	Score RULA Posture 2-NodeX
1	VT from the ground	6	6
2	VT from the platform	3	3
3	VT from the platform and new rotation scheme	2	2

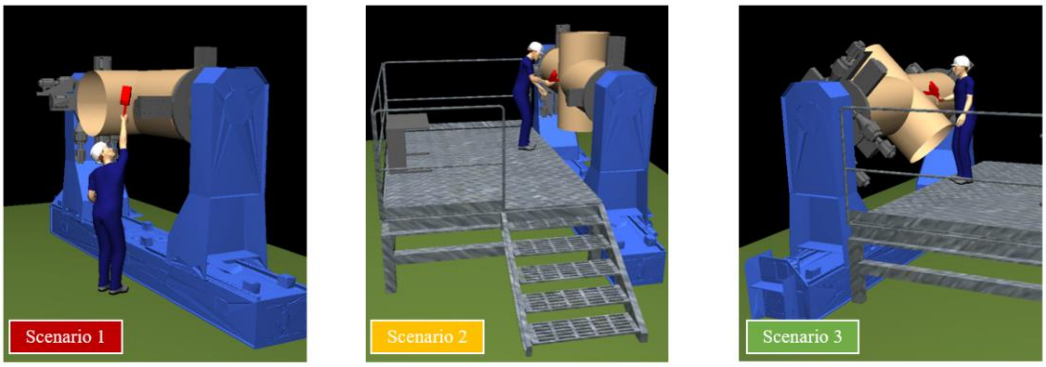

Figure 5. Screenshots of X-nodes scenarios examined in Tecnomatix Jack.

In Scenario 3, the RULA analysis indicated level 1 for the two positions studied, which in turn means that the positions are acceptable if they are not maintained or are repeated for long periods of time. Therefore, we concluded that this scenario is the most ergonomic and thus this configuration will be the one to implement in the workshop for the VT workstation of node X.

The same procedure was applied to the Y node, obtaining the results shown in Table 4.

Table 4. Summary of first results obtained in ergonomic analysis of node Y.

N Scenario	Description	Score RULA Posture 1-NodeY	Score RULA Posture 2-NodeY
1	VT from the ground	7	7
2	VT from the platform	3	5
3	VT from the platform and new rotation scheme	2	2

As in the previous case, the results of the RULA ergonomic analysis of node Y indicated level 1 for the positions studied.

However, when we studied the Y nodes of jackets for offshore wind farms in deeper waters, we detected that it is not feasible to use this type of rotator together with the platform. In other words, we observed that the lower node collides with the platform when rotating the node to inspect the joint weld of the upper stub. This is shown in Figure 6.

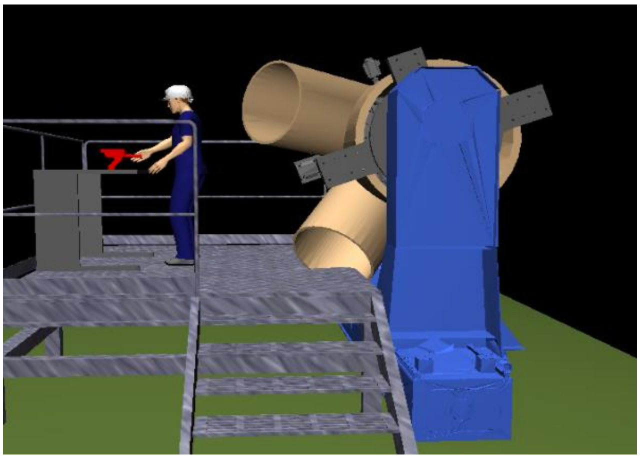

Figure 6. Interception of Y-node with the platform.

In addition to detecting a bad posture in the operators, this ergonomic analysis allowed us to verify how the technology that was intended to be used is valid in the case of node X but not in the case of node Y, where a new solution is needed.

After presenting these results to the NAVANTIA's Engineering Department, the Y node rotator was modified so that the node is rotated along the z axis as shown in Figure 7.

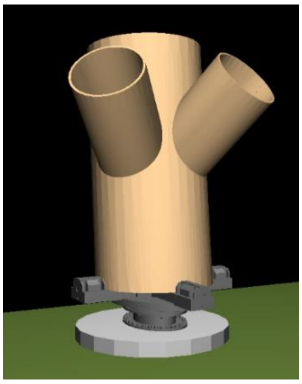

Figure 7. New Y-node rotator design.

For this new rotation system, we also carried out an ergonomic analysis starting from a model without a platform and further checking if it is necessary to use a platform or some extra auxiliary system. The scenarios that we contemplated were:

- Scenario 1: The most unfavorable case in which the operator performs the inspection from the ground.
- Scenario 2: An intermediate scenario in which we incorporated a platform to lift the operator which allows him to inspect the top of the joints. Yet the inspection of the lower zone is carried out from the ground.
- Scenario 3: The most ergonomic scenario. It includes two platforms, one higher than the other, so that the operator has entire access to the inspection area while always keeping a suitable posture.

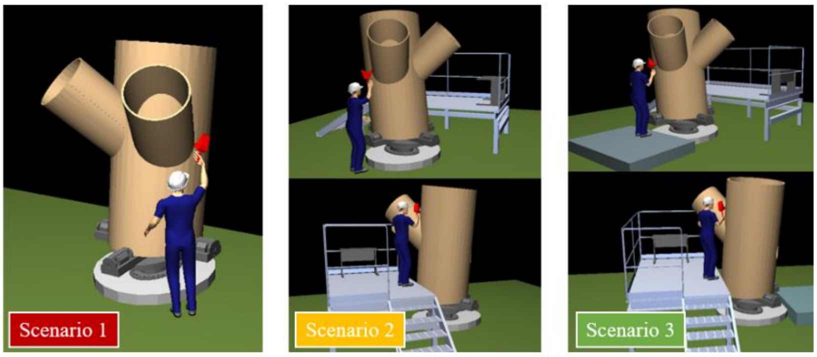

Figure 8. Screenshots of Y-nodes scenarios examined in Tecnomatix Jack.

Error! Reference source not found. shows the results of the RULA analysis obtained in the three scenarios of the new Y-node rotator. Posture 1 corresponds to the inspection of the lower area and posture 2 to the upper part. Since in scenario 1 we did not contemplate the use of any platform, the operator cannot reach the highest zones and therefore we could not perform the ergonomic analysis.

Table 5. Summary of final results obtained in ergonomic analysis of node Y.

N Scenario	Description	Score RULA Posture 1-NodeY	Score RULA Posture 2-NodeY
1	VT from the ground	7	-
2	VT from the ground and platform	3	3
3	VT from two platform	2	2

Therefore, we observed how stage 3 is the most ergonomic since a score of 2 is obtained in both positions, which corresponds to a level 1 in the RULA analysis.

Finally, we set up the new proposed node's rotation scheme back again in FlexSim so that we obtained a final 3D animation of the noticed operation integrated with the process simulation (Fig. 10).

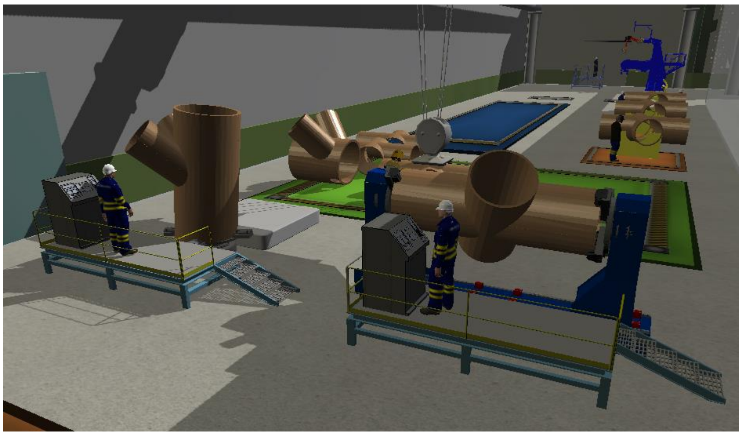
Figure 10. Node's inspection animation after the ergonomic study.

5. CONCLUSIONS

In this paper we presented an innovative approach that consists of the use of the 3D DES FlexSim software together with the ergonomics software Tecnomatix Jack from Siemens to carry out the study and design of the VT process of a new robotized workshop of jacket nodes for NAVANTIA S.A. The study was undertaken both from a production and an ergonomic point of view.

Once we developed the 3D model of the new automated workshop, we studied the NDT process and brought in a new solution for VT in accordance with NAVANTIA’s personnel based on a node adjustable rotator and a new inspection system. This allowed us to reduce the number of stations required, as well as the task time and variability with respect to traditional NDT. Furthermore, the implementation of detailed 3D animations in FlexSim raised the need for an in-depth analysis of the operator's task performance from an ergonomic point of view.

We then used Tecnomatix Jack to perform ergonomic analysis using the RULA method and proposed much more ergonomic alternatives. In the case of X-node, the new design of the station includes a platform to lift the operator along with a redefinition of the rotation trajectories of the node. On the other hand, in the Y-node station we detected, beyond the ergonomic factors, that the rotator design was not valid for all Y-nodes, as in the larger ones the stubs collided with the platform and prevent the turn from taking place. To solve this setback, the results were presented to NAVANTIA’s Engineering Department, who modified the design of the rotator so that now the node is placed vertically, and therefore this issue avoided. Once we adopted this new approach for the Y-node, we carried out new ergonomic analysis from which we concluded that it is necessary to have two platforms, one higher for the inspection of the upper zone of the weld, and another one placed lower for the rest of areas. Finally, we incorporate all these changes into 3D animation in FlexSim, thus obtaining a final integrated model.

Overall, this case study primarily puts forward the potential use of 3D DES to assess task performance by humans through detailed 3D animations in the design stages of a process. However, it also places the need for external human-simulation software to evaluate them from an ergonomic point of view so that afterwards the results may be reflected again in the 3D DES software. Consequently, this iterative approach allows optimizing a task or process by adopting a human-centered perspective while considering productivity analysis and the most optimal technology for the workstation.

Acknowledgment

The authors are thankful to the joint venture Navantia-University of A Coruña (UMI) and Navantia for their valuable support.

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