

Interactive simulations as a tool for logistics and maintenance of IFMIF-DONES

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ABSTRACT

Pre-configured virtual reality (VR) simulations of the logistics and maintenance processes have proven to be useful for identifying potential design issues as well as planning operations during an early design phase of facility. But VR simulations can also be used to deeply explore the feasibility of these procedures in a more interactive manner, so that we can identify potential risks and difficulty levels from early stages and study different maintenance strategies to assist the maintenance worker during these procedures. This article presents a framework to design and validate logistics and maintenance procedures in complex facilities, such as the International Fusion Materials Irradiation Facility DEMO Oriented Neutron Source (IFMIF-DONES). Our framework begins with a preparatory phase where essential information about the procedures and Computer-Aided Design (CAD) models is compiled into a comprehensive Virtualization Task Document (VTD). Differently from previous work, this VTD allows representation of parallel tasks. We implement the interactive version of the virtual environment, where the different maintenance and logistics equipment, as well as a virtual maintenance worker is controlled by the user (the person executing the interactive simulation). We have validated this interactive framework with two simulations for the installation process of the Superconducting Radio Frequency Linear accelerator (SRF Linac) modules in IFMIF-DONES. In one simulation (the automatic one), the procedures are reproduced as they are planned, while in the second simulation (the interactive one) the user freely controls the movements of the moving parts of the crane, grab and release plant equipment, move platforms, etc. Based on our simulations, the interactive version allows easier detection of potential points of collisions as well as more precise assessment of the difficulty of the tasks to be performed.

1. Introduction

IFMIF-DONES is an experimental facility designed to study and develop materials for future fusion reactors projects [1]. The facility is classified as a radiological facility, differently from a nuclear facility. This facility will include a high-energy neutron source to be used to irradiate materials to assess their performance and degradation over time. From an engineering point of view, IFMIF-DONES will be a complex facility, including difficult installation procedures with heavy (several-tons) pieces of plant equipment and periodic maintenance operations of high complexity in a hazardous environment. Aiming to optimize the rate of operation time and running costs, it is necessary to carefully plan how and when these operations will take place. Particularly, in the area of 'Logistics and Maintenance' of the project, the main goal is to detect inconsistencies in the designs, before it is considered

definitive [2].

In IFMIF-DONES, the main logistics and maintenance operations have been virtualized in the last years [3]. These simulations are based on commercial game engines (such as Unity or Unreal Engine). Although these tools were designed mainly for the development of video games, they have demonstrated their value also for other fusion-related facilities [4–6] thanks to their high flexibility and ability to produce realistic outcomes during the initial design stages. For instance, in the context of validating the installation and removal processes of sealing interfaces at the Vacuum Vessel ports within the ITER (International Thermonuclear Experimental Reactor) project [4], simulations are visualized utilizing Head Mounted Displays (HMDs). The simulated tasks there predominantly involve manual, hands-on operations. An analogous situation arises in the context of replacement operations for Test Blanket Modules within the framework of Air-Fed suits [5]. This circumstance

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underscores the significance of investigating operator ergonomics, the effective management of hoses, and a comprehensive examination of the operator's field of view throughout the operational process.

In this regard, it is noteworthy that the preceding body of literature exhibits well-established procedures. However, it is essential to recognize that within the context of logistics and maintenance operations associated with IFMIF-DONES, there exists a degree of variability contingent upon factors such as modifications in building or plant equipment designs, among others.

Previous simulations of logistics and maintenance operations in IFMIF-DONES were based on a well-defined sequence of steps oriented to reproduce the previously established procedures [2]. This *static* approach, although useful to carefully explore the plant and possible maintenance / plant equipment inconsistencies, demonstrated to be limited during the early stages of maintenance procedure design as it required a considerable amount of development time from specialized personnel to arrive at a preliminary procedure into a simulation. Similarly, every modification of a pre-established procedure required additional development time.

Aiming to overcome these limitations, in this article we propose a tool of interactive simulations for analysis of logistic and maintenance operations in IFMIF-DONES. By allowing the designer of logistic procedures and maintenance tasks to freely operate the different pieces of maintenance equipment, these simulations enable obtaining a fast general insight of the best way to perform such tasks, exploring different alternatives and providing agile feedback.

Within this paper, we delineate the transformation of our static simulations into interactive simulations in Section 2, explaining the workflow of how to create them. Moreover, in Section 3 of this article it is described the proposed methodology to create the interactive simulation of the installation of the SRF Linac Module 5, a relevant part of the accelerator system in IFMIF-DONES. In Section 4, we unveil the results we have garnered while assessing the utility of this tool. Section 5 then hosts an in-depth discussion regarding these outcomes. Finally, in Section 6, we present some conclusions while also outlining avenues for future research.

2. Simulation of logistics and maintenance operations in IFMIF-DONES

This section explains how the procedure to obtain virtual reality simulations has been modified to also consider interactive simulations in which the designer is allowed to operate the plant equipment.

2.1. Transforming logistics and maintenance descriptions into a virtualization task document (VTD)

The comprehensive delineation of logistics and maintenance steps stands as a pivotal milestone for confirming the viability of the procedures. The process of creation of the simulations starts with the

gathering of information about procedures and CAD models implied (Fig. 1). This information is transferred into a tool to facilitate interaction between teams, the Virtualization Task Document (VTD). This tool was defined in a previous paper [2], but for the goals of this work, the tool has undergone substantial changes due to the nature of the interactive simulations.

While our previous study considered a pre-defined sequence of steps for every task and sub-task, for interactive simulations the suggested sequence of these steps is inherently flexible, allowing their execution in any order.

In addition to this, and aiming to allow parallel operation of multiple pieces of maintenance and logistics equipment, we now separate the operations performed and related to different simulated elements into different Microsoft Excel sheet tabs. In each tab, we follow the same structure defined in our previous paper about the level of detail of each step (Fig. 2).

Aiming to ensure the coherence of the operation between multiple pieces of maintenance and logistics equipment we also introduce a flowchart where we define the dependencies between the operations performed (Fig. 3). In this tab, every column represents the operations performed with a logistics or maintenance equipment, while the arrows indicate that, the task at the origin of the arrow must be finished before starting the post-arrow task. For the sake of clarity, only level 2 tasks have been represented in this workflow, assuming that there is no dependence between level-3 tasks included in different level-2 tasks.

As an example, the VTD for the installation of the SRF Linac Module 5 is provided as Supplementary Material (SM1).

2.2. Selection of software

Since there are different software environments to develop the simulations, we first performed a comparison between the features, the advantages and the drawbacks of every alternative. We analyzed VR4Robot, Mevea, Unreal Engine and Unity.

VR4Robots is a real-time visualization and simulation tool that provides facilities to display and interact with 3-dimensional computer-generated models of robotic devices and other components in a virtual world [7]. This tool was originally developed for the interactive visualization of the remote handling operations in JET (Joint European Torus) and it supports the main phases in remote handling: equipment and plant design, task development and remote handling task execution.

Mevea is a simulation software that mainly focuses on supporting the implementation of digital twins of heavy machinery. It can be used to optimize performance, reduce downtime and improve safety [8]. Mevea is also compatible with Unity and Unreal Engine for visualization and for the creation of virtual sensors in the simulated environment.

Unreal Engine is a popular game engine that is known for its advanced graphics capabilities. Its main use is to create high-end games with realistic graphics and physics [9]. It has a large community of developers and users, which makes it easy to find help and resources.

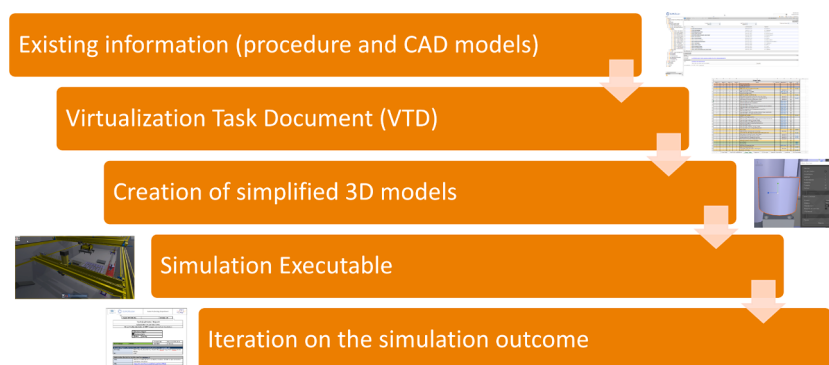


Fig. 1. General workflow to obtain VR simulations in IFMIF-DONES.

Virtual Tasks OMP										
Level 3	Level 2	Level 1	Level 0	Name	Est. Dur.	Equipment ID	Version	State	EH-ID	C-ID
0	0	0	0	Initial Conditions				OG	#E1000	
1	0	0	0	Installation of SRF LINAC module 5				OG		
A	1	0	0	Move OMP to enter room R104				OG		
A	1	1	0	Move OMP through door A				OG	#E1001	
A	1	1	1	OMP goes to Room R104				OG		
A	2	0	0	Move OMP to enter room R105 from room R104				OG		
A	2	2	0	Move OMP through door B						
A	2	2	1	OMP goes to Room R105				OG		
A	3	0	0	Move OMP to enter Accelerator Vault				OG		
A	3	1	0	Move OMP through door C				OG		
A	3	1	1	OMP goes to Accelerator Vault						
A	4	0	0	Position OMP to installation position				OG		
A	4	1	0	Rotate OMP				OG		
A	4	1	1	Rotate 90 degrees						
A	4	1	0	Move OMP next to installation position				OG		
A	4	1	1	OMP goes to installation position						
A	5	0	0	Position OMP to exit Accelerator Vault				OG		
A	5	1	0	Move OMP next to door C				OG		
A	5	1	1	OMP goes to door C entrance						
A	5	2	0	Rotate OMP				OG		
A	5	2	1	Rotate 90 degrees						
A	6	0	0	Move OMP to exit Accelerator Vault				OG		
A	6	1	0	Move OMP through door C				OG		
A	6	1	1	OMP goes to R105						
A	7	0	0	Move OMP to exit room R105				OG		
A	7	2	0	Move OMP through door B						
A	7	2	1	OMP goes to Room R104				OG		
A	8	0	0	Move OMP to exit room R104				OG		
A	8	1	0	Move OMP through door A				OG	#E1001	
A	8	1	1	OMP goes to Shipping bay				OG		

Fig. 2. Example of virtual task description of the Omnidirectional Mobile Platform (OMP) in the VTD. Different colours represent different levels of abstraction in the task hierarchy. The blue rows correspond to level-2 tasks (the most general tasks), the yellow ones correspond to level-1 tasks and the white ones correspond to level-0 tasks. The most detailed steps are level-0 tasks. In orange is the general task name represented here, level-3 tasks.

Unity is a cross-platform game engine that is known for its ease of use and flexibility. It is possible to develop games in 2D or 3D, as well as other interactive experiences [2]. Like Unreal Engine, Unity also has an active community of developers, making it easy to find information.

There are several reasons for selecting Unity over other software options. Firstly, while all of the software options mentioned are paid, Unity and Unreal Engine offer free plans that allow developers to use the tool with the only restriction to pay a percentage of the revenues when your application reaches the royalty threshold. However, since these applications are intended to be used for a restricted community (order of hundreds of users), these royalties are not applied.

Secondly, the compatibility with widely-used CAD design tools. Unity counts with the PiXYZ plugin, which enables reduction and optimization of mesh models. It allows the developers to import models with different formats that are not natively compatible with Unity, remesh models, and simplify them, among other features.

Another feature that could be useful for the project is the possibility to export the simulation into different platforms. With Unity or Unreal we could easily create PC-based simulations for Windows, Mac or Linux, modify it to be compatible with Head Mounted Displays (HMD) or create a server application that runs the simulation.

Finally, the decision was made to use Unity as our software tool rather than other options. However, the chosen platform may change over time, when new platforms might be released or because of different requirements for the simulations. For example, while Unity has its own physics system, Mevea could be used in the future for a more complex simulation, because Mevea is the one that cares about physics and input controls of the simulation. In any case, the design principles presented in this article could be extrapolated to simulations made with different tools.

2.3. Formats and performance in the simulation

We typically receive the designs in one of the common CAD file formats for mechatronic designs (STEP and CATIA files mainly). These file formats are not directly compatible with Unity Engine, which only accepts with fbx, dae, 3ds, dxf and obj files. However, by using the PiXYZ plugin we can also import the STEP and CATIA files.

It is important to note that the simulation runs smoothly on the computer. In general, we try to achieve at least 60 Frames Per Second (FPS) for the simulations. To do that, we simplify the 3D models we

received. For example, originally, the SRF Linac Module 5 3D model had 3.372.528 triangles and we managed to reduce it to 2.641.218 triangles, 21 % of reduction. Finally, the whole simulation has 26 million triangles, but there are some parts of the models which are not rendered during all the simulation time, since we are using occlusion culling. Occlusion culling is a feature that disables rendering of objects when they are not currently seen by the camera because they are occluded by other objects. Our performance study was done in two different computers considering renderization 4 cameras at the same time, obtaining the following results:

- MSI Creator 15 laptop with Nvidia GeForce RTX 2080 Super Max-Q Design GPU, Intel(R) Core(TM) i7-10875H CPU 2.30 GHz and 64 GB of RAM. It runs consistently above 88 FPS.
- Desktop Computer with Nvidia GeForce RTX 3090 GPU, Intel(R) Core(TM) i9-10980XE CPU 3.00 GHz and 128 GB of RAM. It runs consistently above 270 FPS.

Both computers include a dedicated graphic card, which is an important piece of hardware for running applications with intensive graphic processing, like this simulation.

2.4. Creation of the interactive simulation executable

In this paper, we are introducing interactive control of the logistics and maintenance equipment that will help us to validate some of the logistics and maintenance procedures. By implementing this new feature, the users (as procedure designers) have the opportunity to test alternative procedures.

Differently to the implementation done in [2] where all the movements were pre-configured before starting the simulation, in this case some of the movements can be defined to perform automatically (with pre-configured trajectories) while other operations must be manually driven by the user. In order to enable manual control of a particular piece of logistics or maintenance equipment, we first need to define which are the degrees-of-freedom (DoF) to be controlled and then associate a DoF of the peripherals to be used for that purpose. Thus, different kinds of human-machine interfaces can be tested for every system, evaluating in this way which one fits better for the particularities of the movements to be performed.

So far, we have implemented the interactive simulations to be

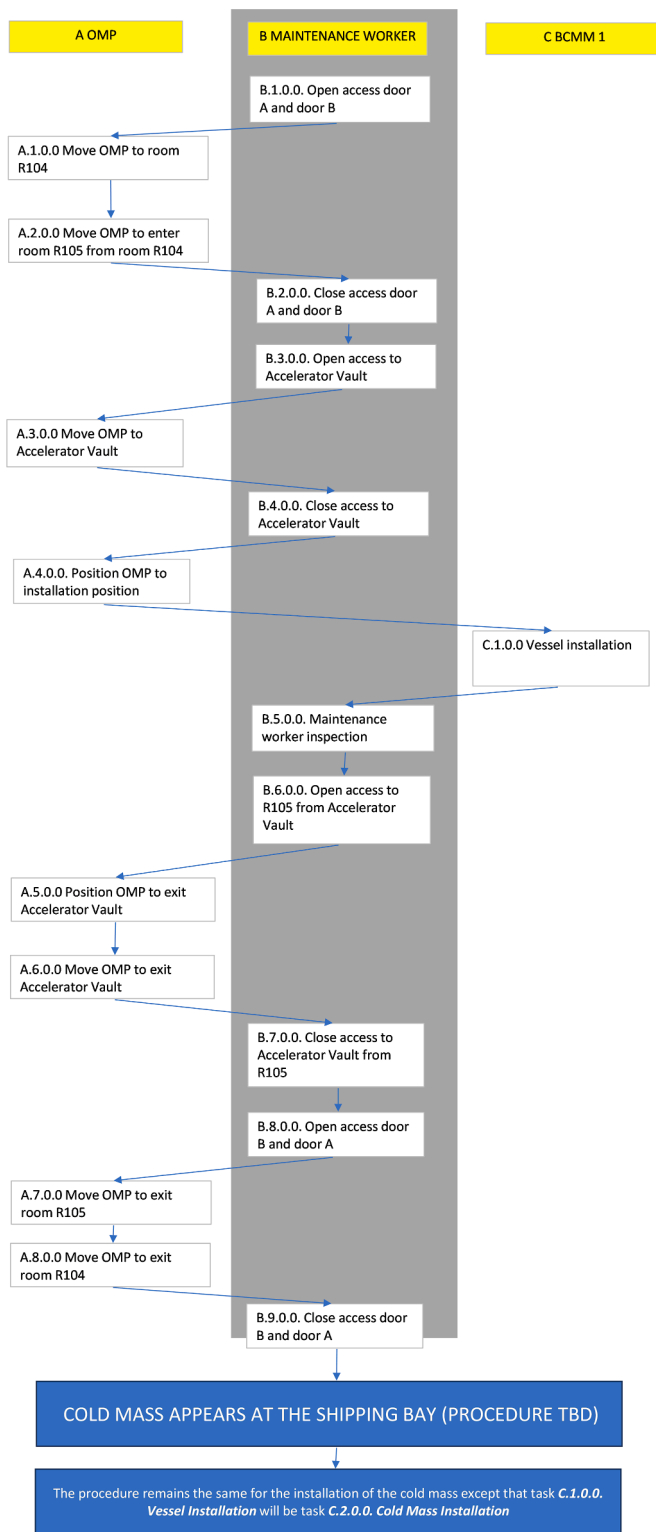


Fig. 3. Flowchart representing the dependencies between level-2 operations for the installation of SRF Linac Module 5. A corresponds to OMP tasks, B to maintenance worker's tasks and C to a crane called Bridge Crane Manual Maintenance 1.

controlled with keyboard and mouse, due to the high availability of these devices. The keyboard has the advantage of providing as many keys as required to assign one pair for each DoF of the logistics/maintenance equipment. However, other hardware devices can be integrated to operate that equipment included in the simulations, like, e.g. joysticks

or haptic devices. In any case, the implementation needs to assign different device buttons or DoFs to particular operations or DoFs of the logistics/maintenance equipment under control. To control the interactive simulation, we created a new pop-up window that allows the user to select which element wants to operate (Fig. 4). In this use case, the user can select the OMP, the Bridge Crane Manual Maintenance 1 (BCMM 1) or the virtual maintenance worker. So far, the user is only allowed to move one of those elements at the same time. However, the implementation is already thought to allow multi-user interaction, where several users will operate different elements simultaneously.

This new implementation allows the designers to explore different movements for each DoF in order to reduce collision risks or to minimize the travel distance or the time required to perform the procedures, and more importantly, to check the feasibility of the execution of the task.

3. Use case: installation process of SRF Linac modules

In order to validate the capability of the developed workflow to produce useful information for the procedure designers the workflow has been applied to the installation of the SRF Linac modules of the accelerator system in IFMIF-DONES. The SRF Linac aims to accelerate the 125 mA CW (Continuous Wave) deuterons beam from 5 MeV to 40 MeV. These components are housed in cryomodules. To minimize the beam losses as well as to meet the 'hands-on maintenance' machine requirements, all the components of the linear accelerator, as well as the distances between adjacent components, are made as short as possible. This led to a very compact design of the accelerator and to a more complex installation process [10].

The interactive simulation of the installation of the SRF Linac Module 5 has been designed with diverse objectives. Firstly, to validate the consistency of the 3D model designs of the building and plant equipment (e.g. to check if the procedures could be accomplished with the up-to-date models and provide feedback about the procedure or the designs). By using this simulation, we aimed to check if the fifth cryomodule fits correctly in the accelerator vault as well as if it can be safely transported through the doors from the shipping bay to the accelerator vault. It means checking any possible collision with walls or other elements in the plant, and to be aware of any dangerous zone or stage during the procedure.

Secondly, this simulation was thought to provide a raw estimation of the time required for the maintenance workers to complete the installation procedure. Other variables that can be measured can also be useful, such as the distance between the elements moving on the plant and the wall.

The interactive simulation tool is used for the analysis of the first installation of a SRF Linac module as well as the replacement of it in case of a failure (assuming the old component has been removed before), so it can be used for logistics analysis and for maintenance analysis.

During the development of the simulations, some details of the procedure were to be decided. For example, in the installation of the fifth cryomodule, the designers were evaluating two alternatives: installation of the module completely assembled or installation of the module in two parts, first the vessel and then the cold mass. This interactive simulation tool allows us to provide feedback about the issues for these two alternative procedures without requiring specific

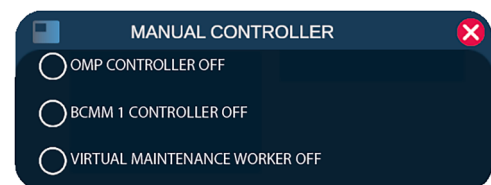


Fig. 4. Manual controller window for selection of the logistics and maintenance equipment to operate or to activate the virtual maintenance worker.

development to reproduce each alternative.

4. Results, Simulation and outcomes

The interactive simulations of the installation of the SRF Linac Module 5 in IFMIF-DONES are provided, together with this article in Supplementary Materials (SM2 and SM3). These simulations provided better understanding of the operations required for this installation.

Our simulations also allowed us to extract a list of recommendations for the building, plant equipment, maintenance equipment and logistics equipment designs concerning some problems that might arise during the transport and installation procedures. Already during the initial analysis of the models, we found that some collisions might happen with the walls (Fig. 5), depending on the final designs of the cold-mass auxiliary supporting structure and the OMP described in [11].

It has to be mentioned that, for this simulation, we modelled a mock-up version of the pallet of the OMP and the cold-mass auxiliary supporting structure (Fig. 6) as there is no final design of these devices yet. However, this simulation already evidences some issues that will have to be considered to avoid possible collisions with the doors or walls.

Throughout the course of procedure evaluation with the interactive simulation, it became evident that spatial orientation within the operation rooms was challenging as the user could feel temporally lost. In response to this issue, a solution was implemented by adding floor-based indicators which were strategically placed to provide explicit guidance delineating the recommended pathway for users, thus mitigating the confusion. (Figs. 7 and 8).

The utilization of interactive simulations enabled us the capability to readily assess diverse trajectories and decision-making scenarios. In contrast to our prior methodology, where modifying a procedure required the creation of a pre-defined simulation along with an executable incorporating updated information or routing, this simulation framework provides an enhanced degree of flexibility in this regard.

In this sense, this simulation has revealed that, when transported a single unit, cold mass and vacuum vessel at the same time, there are movements that can result in significant vibrations and, consequently, a risk of ceramic element breakage. When transporting the cold mass with auxiliary supporting structures, damping elements are incorporated to safeguard the fragile ceramic components, adding more length to the set.

One of the main goals of the simulation was to decide if the assembled module will be transported in two parts or already integrated into a single larger piece.

5. Discussion

During the design phase of a complex installation, such as IFMIF-DONES, multiple CAD tools provide different features in order to obtain a consistent final design of the plant and the operations. Mechatronics CAD tools (such as 3dS Catia ®) allow precise design of the

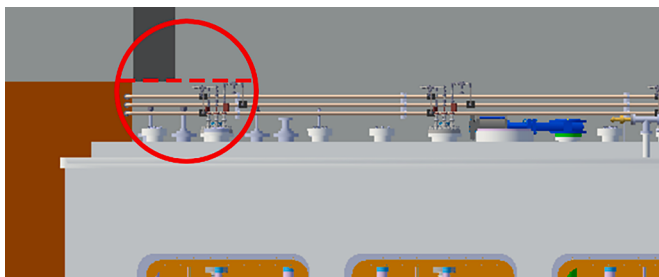


Fig. 5. First analysis of collisions with an old model of the OMP and with the whole module 5 assembled. Small pieces (indicated with a circle) at the top of module 5 could collide with the bottom part of the doorway (indicated with a discontinuous line).

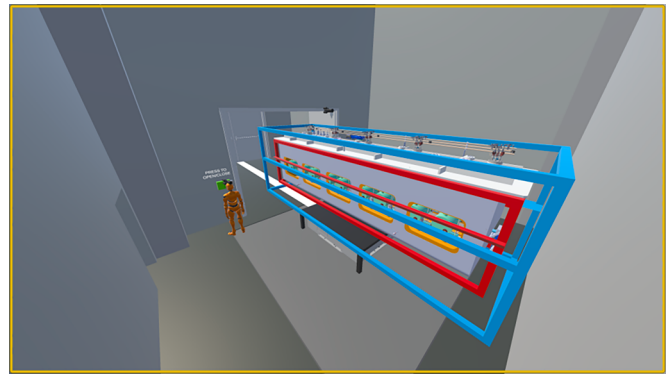


Fig. 6. Mock-up of cold-mass auxiliary supporting structure of the SRF Linac Module 5.

pieces of logistics/maintenance equipment, plant-design tools (such as Autodesk AutoCAD ®) facilitate the representation of the building and system integration tools (such as Autodesk Navisworks ®) enable to validate the coherence of the designs of all these pieces together. However, all these tools provide a static view of the systems involved, meaning that the user could not interact with the systems represented. On the other hand, virtual reality simulations allow the designers to obtain an immersive representation of the interaction between all these pieces. In this framework, the interactive virtual reality simulations enable live representations of installation and replacement of plant equipment even in an early stage of the design of the facility.

In a broader context, this interactive virtual reality tool holds the potential for diverse applications, including, but not limited to:

1. Visualization of 3D models. Our tool provides a detailed version of all the components together, helping in this way to validate these models.
2. Validation of maintenance procedures. Through simulations, a comprehensive understanding of maintenance procedures can be obtained, allowing for the identification of potential issues such as collisions and other operational challenges.
3. Analysis and optimization of the logistics and maintenance procedures. Our tool offers the opportunity to test different alternatives for performing a particular task, facilitating in this way the optimization of the procedure in aspects such as duration or risk in each task.
4. Remote handling operators training: These simulations serve as valuable training tools for potential remote handling operators or maintenance workers, even at a very early stage, enabling them to acquire necessary skills and proficiency prior to engaging in tasks within the actual facility. This represents one of the notable strengths inherent in simulations of this nature, wherein operations involving machinery are seamlessly integrated with virtual maintenance workers.

6. Conclusions and future work

This study represents a substantial upgrade from our earlier development efforts. Now, the user assumes a more proactive role within the simulation, thereby wielding increased agency to effect modifications to both the simulation itself and its maintenance and logistics procedures. This represents a first step towards the implementation of a more adaptable and versatile simulation framework.

The forthcoming stages in the development of interactive simulations encompass the integration of novel visualization and control interfaces, including, but not limited, to Head Mounted Displays (HMDs), haptic devices, various types of joysticks, and control panels, among others.

The present study endeavors to employ this kind of tools for the

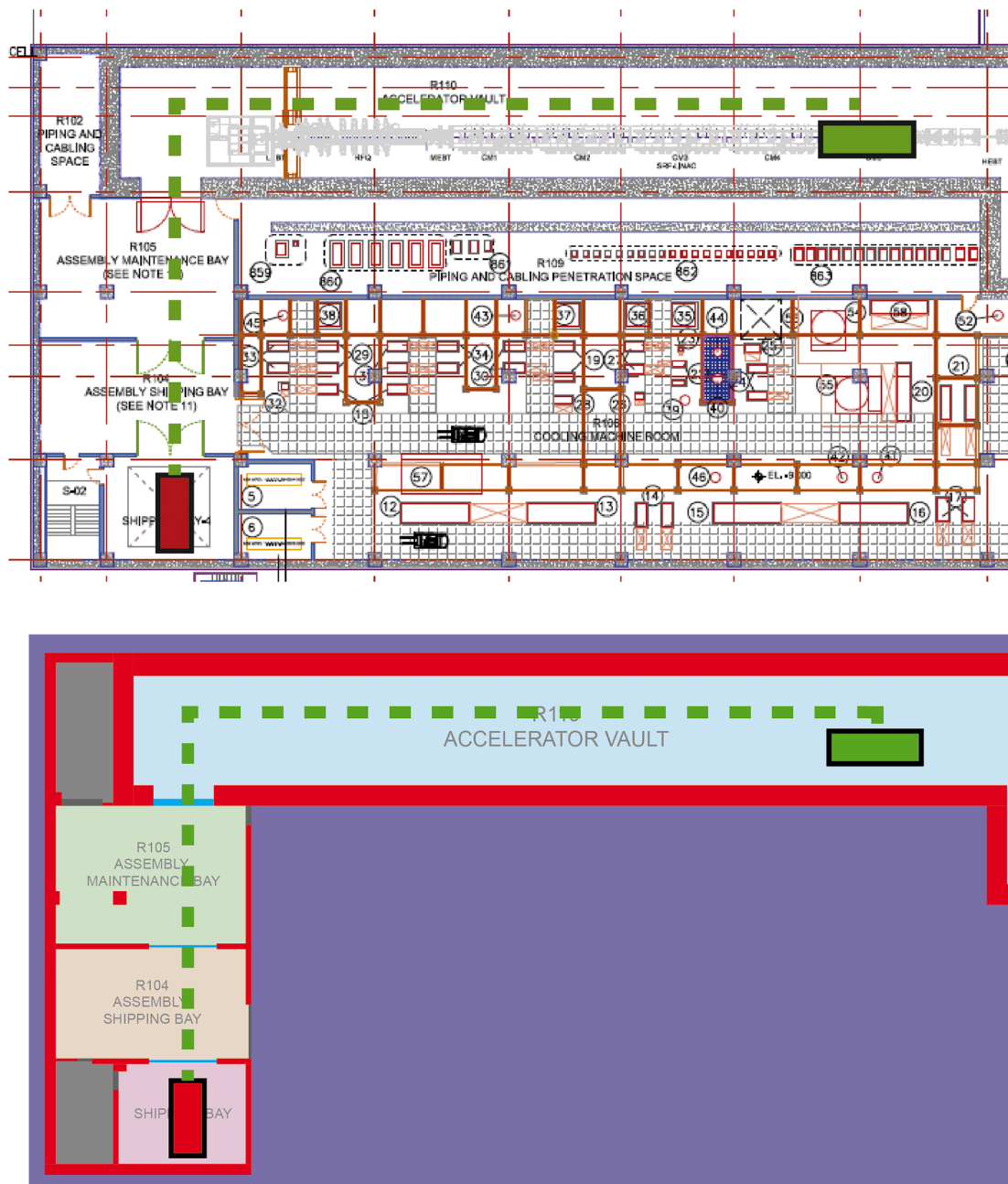


Fig. 7. Planned path to carry out the installation. Green line indicates the trajectory of the module from the Shipping Bay (red box) to the Accelerator Vault (green box). At the top, the original blueprint and, at the bottom, a schematic view of the trajectory to be followed by the module 5.

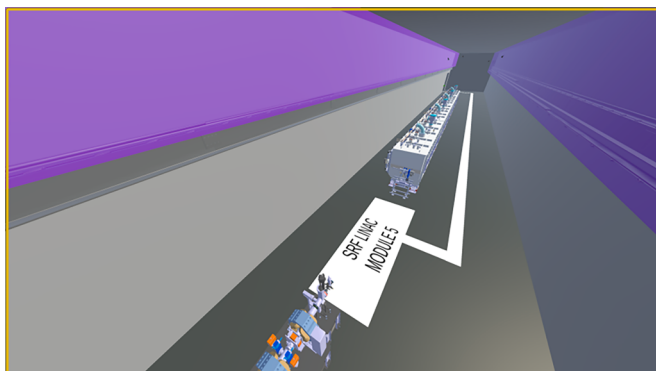


Fig. 8. Suggested guidelines at the floor for better orientation of the users.

purpose of conducting training and evaluation of remote handling operators and maintenance workers within the facility. To this end, we aim to devise a comprehensive assessment framework tailored specifically to the operators, wherein various critical factors, including time considerations, risk assessment or other performance metrics will be evaluated.

In addition to this, other features are planned to be included into our simulation framework. This is the case of the collision detection system, able to provide a comprehensive report detailing the precise locations of collision occurrences throughout an interactive simulation process. This feature will significantly enhance our capacity for evaluating user performance and assessing potential operational challenges.

In next stages, we will also develop the capability of incorporation of a multi-user system characterized by distinct roles and responsibilities assigned to individual users, enabling them to emulate real-world work scenarios. Each user will be stationed at a separate workstation,

assuming control over specific logistics/maintenance equipment, requiring inter-user communication and collaboration to achieve the collective task objectives. This setting may serve as a platform for the development of a collaborative simulation-based training system, wherein a hazardous scenario unfolds, and each participant assumes restricted roles and possesses, thereby requiring interdependent cooperation amongst participants [12].

CRediT authorship contribution statement

Andrea Benito-Fuentes: Conceptualization, Investigation, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Fernando Arranz:** Conceptualization, Methodology, Supervision, Validation, Writing – review & editing. **Eduardo Ros:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing. **Jesús A. Garrido:** Conceptualization, Funding acquisition, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.fusengdes.2024.114315](https://doi.org/10.1016/j.fusengdes.2024.114315).

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