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Logistics and maintenance: current status in the IFMIF DONES project

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Abstract

This article explains the tasks carried out within the logistics and maintenance scope of the IFMIF DONES project, which have been funded by EUROfusion. It was a challenging endeavor due to fact that IFMIF DONES is a first of a kind facility, given its irradiation characteristics. Moreover, the equipment it comprises is a combination of scientific prototypes and conventional auxiliary equipment. Additionally, its operational cycle focused on material irradiation campaigns, is entirely different from typical industrial production cycles. There are three main lines of work (virtual reality (VR) tools, maintenance policy and logistics), although the three of them are coordinated and consistent in content with one another. The VR tools section explains the tools developed using a video-game engine to analyze in detail certain critical maintenance operations. It includes simulations with programmed movements, virtual visits of the facility, and finally, interactive simulations in which the user operates virtual equipment such as bridge cranes or transport platforms using peripheral devices. There is a section dedicated to the maintenance policy, which explains the maintenance objectives, the contents of the developed Maintenance Manual, and the features compiled for preventive maintenance operations, which are organized in a spreadsheet referred to as the Maintenance Matrix. Lastly, there is a section dedicated to logistics in IFMIF DONES. This section explains and justifies the choice of modular omnidirectional platforms for transportation within the main building. It also outlines the solutions identified for transportation between buildings, and handling of certain extremely heavy elements. A subsection is included where the interaction of transport with architectural features is analyzed and proposals for removing clashes produced. Finally, the results of examination of the first installation and the commissioning phase of certain key equipment are described.

Keywords: logistics, maintenance, IFMIF DONES, virtual simulation

(Some figures may appear in colour only in the online journal)

[a] See the Appendix in Ibarra *et al* (https://doi.org/10.1088/1741-4326/adb864) for the EUROfusion WPENS Team
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1. Introduction

In this article, we describe the results of the tasks carried out within the Work Package Early Neutron Source (WPENS) project in the field of logistics and maintenance for the International Materials Irradiation Facility Demo Oriented Neutron Source (IFMIF DONES) plant. The main objective was providing the necessary information for the modification of the building that makes feasible the transportation and handling of equipment during the installation and operation of the plant. Some tasks have also been carried out to define the maintenance policy that ensures the preservation of safety conditions throughout the life of the facility and aim the achievement of the target availability (70% operational availability). The main systems making up the facility are described in [1, 2]. The physical assets of the facility are listed in the Plant Breakdown Structure (PBS) of the project, which is available upon demand (contacting the lead author). We provide hereafter a short description of the main building in order to facilitate and put in context the information included in the next sections.

Figure 1 shows a partial section of the main building with some of the key elements considered for the logistics and maintenance operations. The basement floor hosts the lithium loop and the rooms where activated failed components are disposed of and introduced in shielded containers. The first floor hosts the linear accelerator and immediately following it, the area were irradiation of samples takes place. The second and fourth floors host equipment providing the necessary services and workshops supporting the operation and maintenance of the facility. Three freight elevators allow the vertical transport of equipment between different floors and in particular with the entry points for spares. Activated material can leave the main building after proper radioprotection control through a loading area.

The logistics and maintenance analysis for IFMIF DONES has been conducted simultaneously with the definition of the building and plant systems (B&PSs). As early as 2019, the first analyses were published, including the initial drafts of material flow and spare parts management [3], based on the information available at that time. The work carried out from that time until 2022 is published in [4], including additional concepts such as the Maintenance Matrix, FMEA analyses during maintenance operations, and the first advances in virtual reality (VR) simulations. In the next sections we include the update and improvement of these activities up to 2024, providing an overview of them and adding the new results of our research.

The activities in the area of logistics and maintenance have been structured into three main parts: (1) VR tools, (2) maintenance policy, and (3) logistics. These parts correspond to the sections the reader will find in the main body of the article, but they have not been carried out in isolation; rather, they have been coordinated with each other and with the rest of the areas of the project. In addition to regular meetings (weekly or biweekly) with the coordinator of the respective work team, a quarterly meeting between the different areas allowed for discussions on interfaces and design changes.

Research in VR tools is experiencing a surge in development with diverse applications in the simulation of maintenance for nuclear fusion research plants (ITER, WEST, DEMO, etc.) [5–8]. The use of game engines and hardware such as motion tracking systems, haptic devices, and VR headsets at affordable prices has largely replaced the use of costly physical models. We describe the tools developed in our project in section 2.

The maintenance policy for complex research facilities like CERN has been the subject of research [9], providing invaluable experience for our case, due to significant similarities in big research facilities. Also useful due to their common feature of radiological safety are the studies on nuclear power plants [10]. The latter reference mentions the use of Petri nets as one of the most modern tools in modeling, and we have just begun using this methodology, with some results already published [11]. We describe the work we have done with respect to maintenance policy in section 3.

Regarding logistics, the modeling of transportation in radiation facilities is the main topic in several interesting articles on DEMO [12–14], which analyze the use of software tools and define a systematic way of gathering the necessary information to optimize the design of the facility. In turn, publication [15] analyzes the transportation of activated elements in a precursor project to IFMIF DONES, in the context of the 'Broader Approach,' which is a collaboration between Japan and the EU on various nuclear fusion projects. We describe our work related to logistics in section 4.

2. VR tools

2.1. Task presentation and challenges

VR tools are increasingly being utilized in the design and validation of logistics and maintenance tasks within complex industrial infrastructures [16–18]. These tools offer immersive, interactive simulations of the real-world environment, enabling engineers to visualize, design, and test logistic strategies and maintenance tasks in a safe and controlled setting from a very early stage of design [19]. By replicating the intricate details of complex infrastructures, VR allows for the identification and mitigation of potential issues before they occur in the physical world. Furthermore, in a later stage, closer to the operation of the facility, VR provides a platform for training personnel, enhancing their understanding of the infrastructure and improving their ability to respond to real-world scenarios [20]. Thus, the integration of VR tools in the industrial sector not only optimizes logistics and maintenance tasks but also contributes to the overall safety and efficiency of these complex systems.

The European Spallation Source (ESS) provides valuable insights into the integration of virtual models with real-world testing in Remote Handling environments. Specifically in [21], the authors discuss the comparison between simulations and

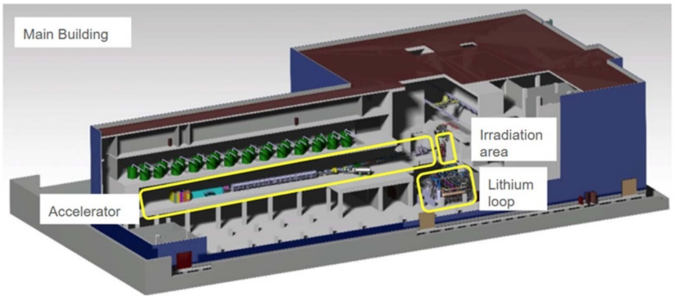

Figure 1. Simplified view of main building and some key equipment location.

physical trials with constructed equipment, allowing for the evaluation of tool effectiveness and task optimization. These insights will be applicable to the hot cells in IFMIF-DONES (still under development), where activated samples will be processed and prepared for transportation.

The facilities for research in nuclear fusion have also incorporated VR tools. For International Thermonuclear Experimental Reactor (ITER), the research institution CEA IRFM has produced analysis tools for complex manual operations. One of these tools follows the position of the VR headset to locate the avatar representing the maintenance worker [5]. This tool, complemented with a vibrotactile arm suit provides feedback to the user for manual operations in tight spaces for WEST tokamak. The same institution applied Augmented Reality and proposed a procedure for the qualification of the design concerning maintainability in [7], including representation of an avatar wearing autonomous breeding suit for manual operations in a contaminated environment. Also for ITER, Heemskerk Innovative Technology simulated a detailed manual procedure and a virtual environment where the avatar of the VR headset user executes manual operations [8]. The analysis of this simulation prompted changes in the design and the environment in order to render the operation feasible.

Feasibility of operations requiring uncomfortable positions of the maintenance worker are analyzed in [6], also proposals for improvement in equipment reachability were reported.

Planning maintenance interventions at CERN has also used simulations combining a CAD design with the spatial distribution of radiation dose rate [18]. In this case, the trajectory of the workers and the residence time at certain points are modifiable parameters. They include a detailed description of the manual operations and a sensible estimate of the time required for each of them, which leads to a reliable estimate of the accumulated effective dose. A comparable methodology was employed in [22], where VR was utilized to optimize maintenance planning for the Joint European Tokamak (JET) fusion reactor. By integrating virtual simulations with dose maps, the study demonstrated how VR can assist operators in identifying high-radiation areas and refining procedural workflows to minimize exposure. This approach underscores the potential of immersive technologies in enhancing safety and efficiency within hazardous operational environments.

In line with the previously referred research, IFMIF DONES is also using the support from VR tools to overcome the challenges emerged during its design. So far, the maintenance tasks of the main systems (such as the accelerator and the test systems (TSs)) have been simulated in order to validate its feasibility. VR simulations have been developed from the beginning of the design of the facility. They were initiated with programmed displacements (section 2.2) where the moving parts have a defined trajectory. It was followed with the development of virtual visits (section 2.3) that allow the user to move a camera around the facility and open and close shieldings. A posterior task within the Eurofusion program included an interactive simulation that allows the user to move equipment such as a crane or a mobile platform (section 2.4). Current and future research activities regarding VR simulations are described afterwards (section 2.5).

2.2. VR simulations with programmed movements

The first activity undertaken by the VALERIA lab at the University of Granada concerning logistics and maintenance was the replacement of the HEBT scraper. This element is activated and it is enclosed in a shielding that can be opened with a teleoperated hydraulic cylinder. Some operations are done manually (before opening the shielding or after removing the activated component) whereas others are done with remote handling equipment. The exchange of information between plant equipment designers (HEBT scraper), maintenance equipment designers (e.g. crane) and VR simulation producers, was materialized through a document called virtualization task documentation (VTD). The contents and the use of this document is explained in detail in [23]. Also the systematic procedure to translate the high-level information of VTD into a node graph readable by the software to produce the simulation (Unity 3D) is described in the same reference.

The replacement of the RIR module was a posterior simulation. This module is located in an area where dose rates would allow only short periods of manual maintenance operations. In this case, the simulation was improved and completed with some additional features included in the executable file. The first addition is the creation of a handbook with the instructions for the user of the simulation; this pdf file is downloaded together with the executable and explains in detail the functions implemented as well as offering links for explanatory videos. This facilitated enormously the use of the simulation by people of the project that may profit from its use.

The camera system was also further developed, offering now the following options (figure 2):

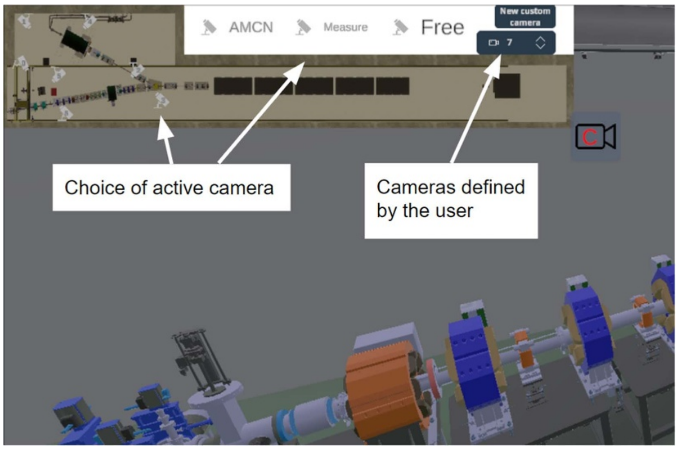

Figure 2. Selection area for the camera system.

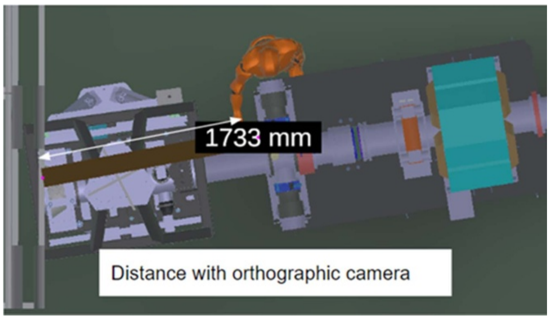

Figure 3. Distance with orthographic camera at a point of interest of the simulation.

- AMCN camera: changes the view to the camera positioned on the Telescopic Mast of the crane known as AMCN. This camera proved to be very useful for observation of the crane grasping tools or engaging the module to be replaced.
- Measure camera (figure 3): changes the view into an orthographic view and enables the measure distance tool. Three orthogonal orientations can be chosen, and the depth of the plane at which the measure is taken.
- Free camera: enables the user to move around a camera as if it was flying on top of a drone. Meanwhile the simulation can be either running or stopped. This camera was extremely useful to observe operations from different points of view and from different distances.
- Custom camera: creates a new camera. It can be moved around like the Free camera, but then, clicking the space bar, the camera becomes fixed and it is added to a list of 'New custom cameras', such that it can be chosen later on, as any other camera.

Additionally, clicking on each camera a dropdown list appears where the user can choose from three models of cameras: default, Mirion Hyperion compact wide angle and Mirion Hyperion compact narrow angle. A selection button below enables the yaw and pitch rotations of the camera using the keys: Q, E, W, S (figure 4). The cameras with their characteristic field-of-view were included to check the models under consideration for future purchase and installation.

The outcomes of this simulation prompted changes in the design of some components: (1) the bolts of the transport box were too close to the adjacent elements, making it difficult the operation with the nutrunner installed in the robotic arm, (2) the free height of the crane was not enough to extract the new module from the transport box, (3) the lifting movement of the module led to clashes with neighboring elements, (4) the position of the shock absorbers of the crane did not allow enough margin for the target position of the crane. This information was passed as feedback to the designers that will modify the equipment conveniently.

A video showing the main features of the app is available in the following link: https://valeria.ugr.es/NuclearFusion/PredefinedSimulationsNF.mp4.

2.3. Virtual visits

The second group of activities carried out by VALERIA lab included the production of an app that allows virtual visits of the facility. The main objectives of such app are: (1) provide an immersive experience for engineers designing the building, the equipment and the services, (2) facilitate a realistic plan of installation and maintenance of plant equipment, and (3) make the plant accessible to other researchers and the general public.

The three objectives have been achieved successfully and especially the third one. The app can be accessed from a VR headset which provides a very realistic view of the equipment. During different diffusion events, the general public got a good impression of the detailed design of the IFMIF DONES facility.

The app includes the model of three key rooms in the facility: the main room of the accelerator, the room with the cooling systems and the room with the radiofrequency power stations. In these rooms, the user can move around in three different ways:

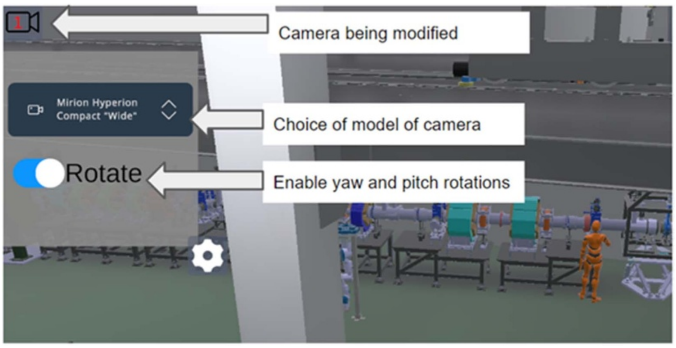

Figure 4. Selection area for modification of features of each camera.

- Normal mode: there is a first person view that moves around as if a camera was moving at 1.7 m of height from the floor. Displacements and rotations can be executed with keystrokes or with the controls of the VR headset.
- Teleport mode: in this case a plant view of the room allows the user to choose a different point, then it locates the avatar there instantaneously.
- Drone mode: in this mode, the camera moves as if it was riding a drone. Again displacements and rotations can be executed with key strokes or the controls of the VR headset, and the height of the camera can change.

The app provides some differences with respect to similar commercial tools like Naviswork or CATIA. The most relevant additions are:

- Information textbox for each plant equipment included in the model (figure 5). While navigating the facility in normal mode, getting close and looking at an equipment activates a yellow outline and an informative text pops up offering the possibility of getting information of that equipment clicking on the key 'i'. This information is obtained automatically from a raw csv file collecting the information of the equipment in the room.
- Open or close shielding (figure 5). In addition to the information, if the equipment has a shielding, it can be opened by clicking on the key 'o'. That would allow having a look at the assembly inside the shielding.
- Teleportation (figure 6). A small plant view drawing opens, with two selection buttons to quickly reach the desired point and, just by clicking on a point, the visitor is instantaneously located in that point. Just closing the plant view drawing we return to the normal mode.
- Multiuser visit. The virtual visits have already been implemented as a server-client application, so several users from different locations can access the same virtual room and see the avatar of each other in the virtual representation. This could facilitate discussions about equipment or installations.

The outcomes of developing and using this app at the IFMIF DONES project were very positive mainly in two areas:

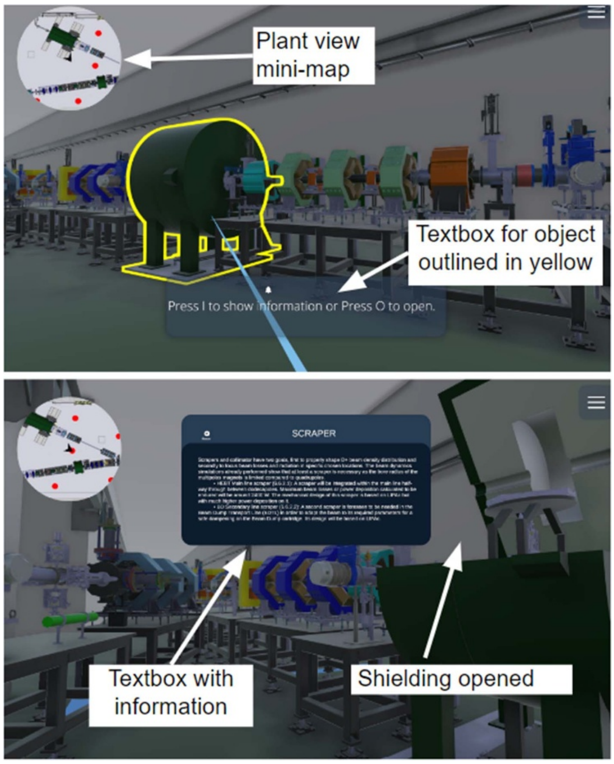

Figure 5. Top: normal visit mode, close to HEBT scraper and looking at it, the perimeter outlines in yellow and a textbox indicates how to get information and open it. Bottom: the visitor has opened the shielding and activated the information text.

first, internal use for discussion for example about the cable trays and HVAC conduits in the main room of the accelerator. The second area was the discussion among maintenance engineers for the access to different elements, like the HEBT scraper and Beam Dump that reduce the free space once their shieldings are opened. Additionally, as mentioned before, this app using the VR headset is a very attractive way to let the general public know about IFMIF DONES.

A video showing the main features of the app is available in the following link: https://valeria.ugr.es/NuclearFusion/VirtualVisitsNF.mp4.

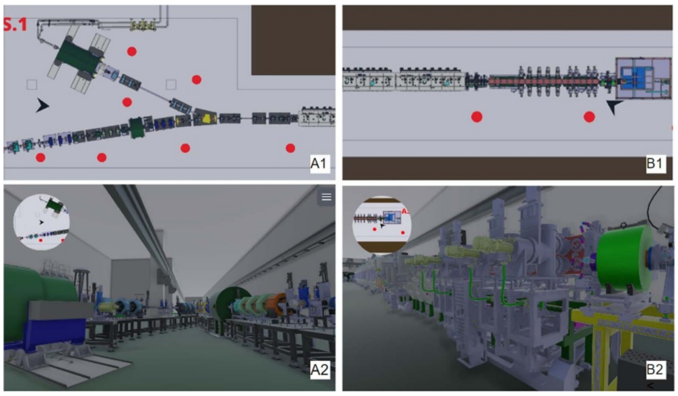

Figure 6. Use of the teleportation feature. (*A1*) choice of location next to the final part of the accelerator, (*A2*) corresponding normal mode. (*B1*) choice of location next to the Injector of the accelerator, (*B2*) corresponding normal mode.

2.4. Interactive simulations

The next logical step in the development of VR tools was the introduction of an interactive simulation, allowing the user to move actionable items at will; this was applied to the installation of an equipment known as SRF Linac module. We developed an app based on a similar procedure than in the case of the HEBT scraper, mentioned in the past section, except that some elements were updated:

- The exchange of information through the VTD document now included a flowchart with the relationship among operations of three actionable elements (bridge crane, omnidirectional mobile platform (OMP) and manikin). The proposed sequence of operations with each element was listed in an independent sheet of an Excel book.
- For each of the actionable elements, the degrees of freedom were defined and a set of keys was defined (see figure 7 for the crane).
- One actionable element could be operated by the user at a time, choosing it from a dropdown list from the menu.
- White lines were represented on the floor as a helper for the displacement of elements.
- When the operated elements were too close to a wall or a static equipment, a change in color warned the user.

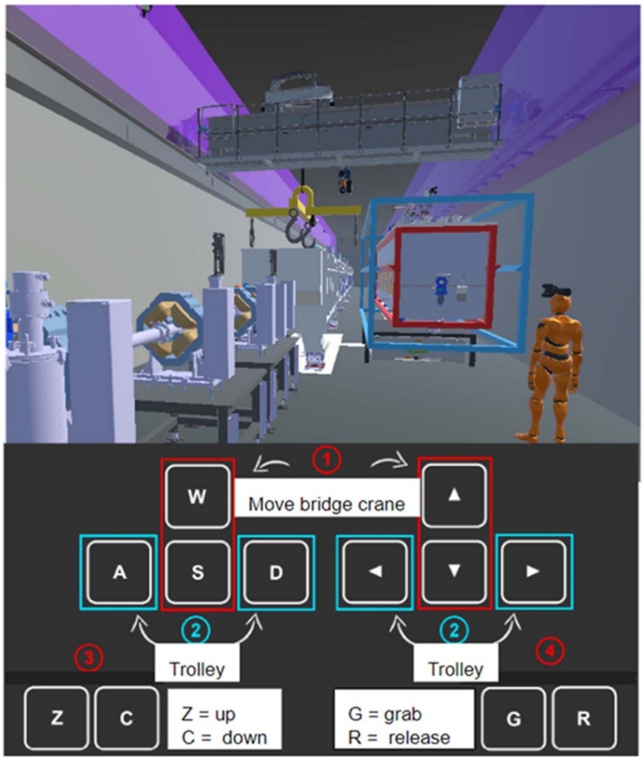

Figure 7. Keys corresponding to the different actions that can be executed with the bridge crane: (1) longitudinal displacement of girder, (2) transverse displacement of trolley, (3) vertical displacement of hooks, (4) open/close teleoperated hooks.

All the other features mentioned in the previous sections were also incorporated into this app: choice of cameras, orientation of cameras, free camera, custom camera, measurement tool, chronometer, etc.

A detailed description of the app can be found in [24], including supplementary materials that are very clarifying. Several modifications and upgrades have been added to the app with respect to the one described in the aforementioned publication. Focusing in a realistic interactive simulation, we have included additional virtual helpers that can be materialized adding instrumentation already available in the market, like for example:

- Laser pointers: they can be fixed to the trolley of the crane, providing very useful feedback to the worker teleoperating it.(figure 8).
- Paint marks on the floor: this inexpensive helper could make the positioning of the element easier and achieve negligible uncertainty (figure 8).
- Tablet for the maintenance worker operating the OMP: the control for teleoperation of the OMP has to be in a short distance, not allowing optimal vision of the opposite side of

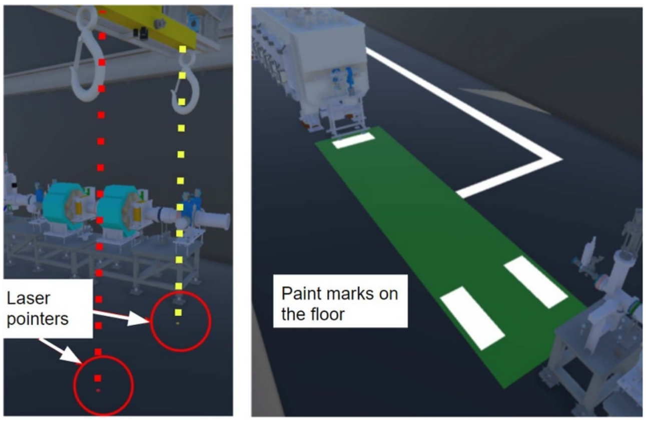

Figure 8. Some helpers were added to the app: left) laser pointers on the crane trolley, right) paint footprint for the installation of the support legs in the right position.

the element being transported. Radio transmission of images from the different cameras installed is a valuable help.

- Onboard distance measurement: laser measurement devices are common instruments used widely in the construction industry. These instruments attached to the load being transported can provide accurate distance that would be really helpful for maneuvering in tight spaces (e.g. rotation of the SRF Linac module inside the accelerator vault).

The current version of this app also includes the option to simultaneously operate the manikin (avatar of the maintenance worker) and one piece of equipment (either the crane or the OMP). This should produce more realistic interactive simulations where the user identifies himself with the manikin and uses the first person view, and with a different set of keys or with a different peripheral (joystick or gamepad), operates the actionable equipment.

A video showing the main features of the app is available in the following link: https://valeria.ugr.es/NuclearFusion/InteractiveSimulationsNF.mp4.

2.5. Conclusions and future development of VR tools

The integration of VR tools in IFMIF-DONES has enabled early and continuous validation of the facility design, adapting flexibly to changes. By creating a unified virtual environment based on CAD models, it has been possible to develop complementary applications encompassing maintenance simulation, logistics validation, and virtual facility exploration. These approaches have allowed us to identify and correct design issues that would have gone unnoticed with traditional tools, optimizing component placement, operation planning, and maintenance task ergonomics. In particular, the simulations have facilitated the detection of interferences in critical maneuvers, improved visibility in teleoperated operations, and assessed accessibility to key equipment. These results highlight the importance of using VR in the development of complex infrastructures, especially in projects still in the design phase, such as IFMIF-DONES.

Over the course of six years conducting VR simulations in IFMIF DONES, we have gleaned several key insights. On one hand, simulations have proven to be an invaluable tool for integrated system analysis, enabling the validation of both CAD designs and planned maintenance and logistic procedures. However, one of the main challenges encountered stems from successive design modifications, which necessitate the continual simplification of models for visualization each time they are updated. In this regard, the use of tools that adhere to the building information modeling (BIM) methodology could represent a significant advancement, allowing for the existence of a single infrastructure model [25]. However, given that this methodology is not yet fully implemented in most of the software tools available on the market, its usage remains still complex.

In the future, the interactive simulation of corrective maintenance operations will be required in order to guarantee successful completion and scheduling of the tasks.

Particular points of interest up for research are: inclusion of dose rate representation and accumulated dose on a manikin representing the worker, implementation of augmented reality mixing real scenarios with virtual representations of elements and automatic generation of movements of actionable equipment based on artificial intelligence tools trained by app users.

3. Maintenance policy

3.1. Introduction to maintenance policy

The maintenance of fusion facilities, and in particular of IFMIF DONES, is a major challenge, mainly due to the large number of prototype systems for which there is no maintenance experience. In this context, the main driver to the maintenance policy of IFMIF DONES is to maximize the operational availability of the facility, with safety as an underlying indispensable requirement. In particular, in terms of availability, IFMIF DONES is planned to have two operational shutdowns per year, a short beam stop of 3 d and a long beam stop of 20 d. Including those planned downtimes, the target is achieving 70% of operational availability. This relatively high availability for a complex facility with some completely new technologies and prototypes can be seen as a challenge in terms of maintenance due to the uncertainty associated with their failure modes. However, it is important to note that there is also a number of maintenance tasks performed on conventional, and, therefore, more predictable equipment, as shown in figure 10. Also, there is a dedicated reliability, availability, maintainability, and inspectability (RAMI) team that is defining design strategies such as redundancies and spare parts stocking policies to enhance operational availability. These will play a key role in achieving the target operational availability target set by IFMIF DONES.

Apart from availability, the following other functions and drivers are also highlighted as relevant for the maintenance of IFMIF DONES:

- Investment protection and cost-effective operation throughout the life of the facility, with the aim of maximizing the lifespan of the asset.
- Efficiency in the use of energy and material resources, always within budgetary limits, promoting sustainable practices that contribute to economic and environmental security.
- Generating maintenance knowledge and improving the existing one throughout the life of the facility, enabling more efficient data-driven management of the maintenance plan.
- Maximizing the impact on the local and regional economy, generating new employment, fostering education and knowledge transfer, and promoting outsourced activities.

It is noted that while safety is not considered a driver of maintenance but rather a requirement, maintenance activities significantly contribute to ensuring safety. In fact, the key safety goal of IFMIF DONES is to guarantee the safety of workers and the environment, carefully following the standards and rules established in the international, national, and regional regulations in force and the relevant documents of the project. These regulations include some guidelines from the Spanish National Nuclear Safety Council (known as the 'CSN', using the acronym in Spanish) and various Spanish National Royal Decrees. Among the project documents, the 'Safety Analysis Report' , is regarded here as a fundamental pillar in terms of maintenance-related safety, establishing the criteria for maintenance operation classification ('hands-on', 'hands-off', or 'remote handling') as a function of the occupational radiation exposure (ORE) of workers, and classifying the physical spaces where maintenance will take place according to the ORE, among other safety relevant aspects. The ORE is adopted as the primary criterion for determining the maintenance operation classification ('hands-on', 'hands-off', or 'remote handling') however other hazards are also considered for such a classification (heavy lifting, high temperatures, etc). It is noted that the areas where these additional hazards are anticipated precisely coincide with the radiation areas in most cases. This spatial correlation of hazards explains why the ORE is adopted as the primary criterion for maintenance classification at this stage. In any case, the as low as reasonably achievable (ALARA) principle is adopted as a key strategy to mitigate the risks associated with radiation and other hazards in the context of IFMIF DONES maintenance.

3.2. Lessons learnt from LIPAc

As mentioned above, the combination of the relatively high operational availability target for IFMIF DONES and, above all, the novelty and the high number of prototypes of the facility, makes the maintenance of IFMIF DONES one of the most challenging research and development areas of the project. In this context, one of the first steps taken in this direction was to reduce this lack of experience by collecting and analyzing the maintenance experience at LIPAc (Linear IFMIF Prototype Accelerator), the sister accelerator of IFMIF DONES, located in Rokkasho, Japan, which is currently in operation (Phase B+).

To this end, the available maintenance documentation from LIPAc was collected and examined, and regular thematic meetings were held between the team effectively executing maintenance in LIPAc and the group in charge of the IFMIF DONES maintenance policy definition. The meetings addressed all relevant issues related to maintenance, including maintenance planning (e.g. conclusions about preventive vs corrective activities), design for maintenance (e.g. foreseeing the space required for maintenance, standardization, etc.), spare parts management, and obsolescence management, among others. The main output of this activity was an agreed list of recommendations and best practices to be implemented in IFMIF DONES. An extract of such a list is given at the end of this section.

In this context, one of the main aspects discussed in this task was the management of the corrective maintenance in LIPAc. We analyzed how the permanent staff that could take care of corrective maintenance could affect the number of workers required during preventive maintenance periods. Specifically, LIPAc has two fixed shutdown periods for preventive maintenance similar to those proposed for IFMIF DONES. However, during operation, various unplanned failures occur that require corrective action, some of which are postponed to the next planned maintenance period (deferred corrective maintenance), if possible. This poses a challenge for the maintenance management team of LIPAc, as they must orchestrate the planning and management of both types of maintenance activities (preventive and corrective) in a coordinated way according to the available maintenance resources and time windows. In particular, one of the main difficulties reported by LIPAc is the frequent overlap of maintenance demand on resources, mainly skilled technicians. For example, some highly skilled technicians are often requested by several maintenance teams at the same time. This leads to bottlenecks and delays that severely impact the overall availability of the facility. To partially solve this issue, their recommendation is to implement a proper corrective action decision workflow that would speed up the process and reduce the downtime of the plant. Through such a corrective action decision workflow, the decision will be efficiently escalated to the responsible person(s) who will decide and coordinate on the optimal schedule, and the need for resources (technicians, spare parts, etc.) will be checked before the action is triggered.

Another important lesson learnt that has been highlighted by LIPAc is the management of obsolescence and the anticipated provisioning of spare parts. For example, if it is planned that an item will be replaced on an annual basis but its procurement time is estimated to be more than one year, or, if the manufacturer will cease to produce an item after a period smaller than its estimated time to failure, an anticipated provision is required. In this context, LIPAc recommends the use of a spare parts management tool that includes information on the planned replacement time of parts and their estimated procurement time, together with RAMI data such as failure rates and time to failure. By combining these data in a rational way using basic reliability analyses, useful information can be obtained about the number of spare parts required and the optimum time to purchase them. It was also suggested that a list of recommended spare parts should be requested from Domestic Agencies and subcontractors supplying equipment and systems to IFMIF DONES. The list of recommended spare parts would ideally be part of the procurement contract and would be updated periodically.

In addition to the useful lessons learned about corrective vs. preventive maintenance and spare parts management explained above, a number of specific recommendations and best practices emerged from the analysis of LIPAc maintenance documentation and the regular meetings held. The following is a non-exhaustive list with a selection of 5 of those recommendations. A complete list of recommendations [26] is available upon request.

- Have a computerized maintenance management system (CMMS) for inventory, maintenance operations records, and maintenance planning, and integrated with event reports, data management system and design and manufacturing history of each component.
- Ensure that there is sufficient space for circulation on each side of the injector and accelerator. To do this, complete the 3D model of the accelerator vault, including all services, and then check the space available for maintenance operations. Suggest criteria for space requirements based on human factors engineering.
- For standard electrical and mechanical equipment (e.g. cables, joints, valves, etc.), try to harmonize components for ease of maintenance and replacement. This includes unifying brands and models as far as possible.
- Avoid the installation of structures (stairs/walkway etc.) that may make access for maintenance or alignment of the accelerator difficult.
- Ensure that component designers incorporate appropriate handling elements when required, particularly for prototype systems. Also analyze the interaction with building systems to check that there is sufficient clearance between the component and the walls to facilitate crane handling.

3.3. Maintenance manual

All knowledge relating to the maintenance of IFMIF DONES, including the policy and strategy, is contained in the Maintenance Manual [27]. This document specifies the guidelines, the regulations and the criteria for the definition of the IFMIF DONES Maintenance Plan, which is a 'living' and continuously updated section within the Maintenance Manual.

3.3.1. Regulations. This section of the manual provides an analysis of the regulations relevant to the maintenance of IFMIF DONES, including those related to radiation as issued by the Spanish National Nuclear Safety Council (known as the 'CSN', using the acronym in Spanish), and other non-radiation regulations establishing statutory provisions for maintenance.

In relation to the radiation-related maintenance activities, and according to the current Spanish Regulation on Nuclear and Radioactive Installations, approved by Royal Decree 1836/1999 and the CSN, the IFMIF-DONES facility can be considered as a first category radioactive installation, belonging to the group of complex installations where very large quantities of radioactive substances are handled or where the radiation beams are generated with very high energy fluence, resulting in a significant potential radiological impact of the installation. This may well be the case for IFMIF DONES, but the terms 'very large', 'very high' and 'significant' are not explicitly described, so further consideration about the category of IFMIF DONES would be expected from the CSN. In any case, as considered in the safety analysis report, a gradual approach has been adopted to determine the level of application and reference of the different regulations during the licensing process.

For the sake of illustration, table 1 below contains a selection of some relevant CSN documents and regulations relating to radiation, with a brief explanation of their provisions relevant to the maintenance of IFMIF DONES. Those can be found in www.csn.es/en/guias-de-seguridad.

The 'Regulations' section of the Manual also specifies the requirements for statutory maintenance for non-radiation related activities. The relevant regulations in this context, along with their provisions relevant to the maintenance of IFMIF DONES, are listed below:

- RD 513/2017 'Fire Protection Installations Regulation' which establishes the specific conditions and requirements for the design, installation and maintenance of fire protection systems in buildings. Annex II of this regulation establishes the minimum maintenance activities that must be carried out on the different fire protection systems, and when they must be carried out. An example of a statutory maintenance activity given in this regulation is the checking of the fire detection and alarm system every 3 months against a specified checklist.
- RD 1027/2007 'Regulation on Thermal Installations in Buildings'. This regulation establishes the technical and maintenance requirements that heating, air conditioning, ventilation and hot water installations must meet to guarantee energy efficiency and comfort. The Technical Instruction 3 within this regulation entitled Maintenance and Usage specifies the statutory maintenance activities of such installations and their periodicity, and stipulates that maintenance operations must be carried out by certified maintenance companies.
- RD 842/2002 'Low Voltage Electrical Installations Regulation' regulates safety in electrical installations, establishing standards for their design, execution, and maintenance. It stipulates, among other statutory maintenance requirements, that the electrical installations of special relevance in low voltage mentioned must undergo inspection right after construction and every 5 year by a Control Entity.

In relation to internal IFMIF DONES regulations and other non-radiological regulations relevant to maintenance,

Table 1. Relevant CSN documents and derived provisions for maintenance.

Regulation title	Provision relevant to maintenance
SAFETY GUIDE 5.8. Bases for preparing the relative information to the exploitation of radioactive facilities	Establishes the obligation to keep an operations diary logbook and the information that should be included in such a logbook. Specifically, all individual doses received by exposed workers, including doses related to accidental or emergency exposures, must be recorded in the logbook.
SAFETY GUIDE 7.6 Contents of the radiological protection manuals for nuclear facilities and radioactive facilities of the nuclear fuel cycle	Establishes criteria for monitoring professionally exposed workers and recording exposure in the dosimetric record. External workers must present a radiological card for data recording. Additionally, it establishes criteria for the classification of personnel and work areas from a radiological perspective, and sets the standards for access, stay, and work in controlled areas.
SAFETY GUIDE 8.1 Physical protection of nuclear materials in nuclear facilities and radioactive facilities	Indicates the implementation of a maintenance program for all systems related to the physical protection of the facility, such as physical barriers, access control, and communications, among others, to secure the effectiveness of the physical protection system.

the Manual provides an exhaustive list of such regulations and their provision to maintenance. This includes regulations related to the protection of the health and safety of workers (e.g. RD 374/2001 and RD 286/2006), the protection against overpressure/vacuum hazards (RD 2060/2008), cryogenic hazards (RD 665/1997), and electric and electromagnetic hazards (RD 299/2016), to cite but a few.

A special mention needs to go to the regulations related to the maintenance of the crane systems, given the extensive use of cranes within the IFMIF DONES facility. The relevant regulations in this context, along with their provisions to the maintenance, are listed below:

- Spanish Technical Notes about Prevention (NTP) 736: this technical note outlines the general conditions for the safe use of overhead cranes, including types, characteristics, parameters, operations, and safety devices. It emphasizes the importance of the adopting the preventive measures and maintenance instructions as given by the manufacturer.
- Spanish Technical Notes about Prevention (NTP) 738: this note focuses on the assembly, installation, and maintenance aspects of overhead cranes from the point of view of risk prevention. It details the preventive maintenance activities that need to be carried out and their frequency.
  - UNE 58144-1:1997: this standard specifies the general requirements for the inspection of lifting equipment with suspended loads. It includes guidelines for regular inspections to ensure the safe operation of cranes.

3.3.2. Maintainable assets. This section of the manual outlines the assets covered by the maintenance plan, comprising the relevant structures, systems and components (SSCs) requiring maintenance, as identified in the PBS of the project.

The PBS of the project, decomposes each SSC into various systems, subsystems and components, uniquely identifying each asset using a six digits code. It also includes a classification of the assets based on their safety and operational importance. For example, based on safety, assets are classified as SIC-1, SIC-2 and No-SIC depending on their impact on radiological safety (SIC-1 assets have more impact than SIC-2). Other attributes of SSCs are explained in section 3.4 when detailing the columns included in the maintenance matrix.

3.3.3. Classification of maintenance activities. This section of the manual describes the types of maintenance activities that will be carried out in IFMIF DONES, together with the means to execute them. With regard to the types of maintenance activities, the manual classifies and therefore names the activities differently according to three independent criteria. These criteria are (1) whether the activities are carried out before or after failure detection, (2) the plant state in which they can be carried out, and (3) the method of execution.

Considering the failure detection criterion, activities are classified as preventive if they are performed before the failure, or as corrective if they are performed after the failure. Within the set of preventive activities, the manual also distinguishes between predetermined maintenance activities, which are carried out according to a predetermined schedule, and condition-based maintenance activities, which are carried out following a diagnosis or prognosis of wear or damage. This classification is consistent with the European standard EN 13306 Maintenance terminology.

According to the Plant state criterion, maintenance activities are classified as maintenance type 1, if the activity can be performed during the planned long beam stop maintenance period, where the lithium loop is also stopped, as maintenance type 2, if the activity can be performed during the planned short beam stop maintenance period, and as maintenance type 3, if the activity can be performed at any time, i.e. during irradiation. This classification applies to preventive maintenance and it is further explained in section 3.4.

Finally, according to the method of execution, the manual classifies the maintenance activities as hands-on, if they involve physical interaction with the maintainable asset (e.g. touching), hands-off, if they require limited contact with the asset, for example applicable to components where the main part of the body or the worker is further than one meter from the surface of the asset during the operation, and remote handling, if they are performed robotically with the worker far away from the asset to avoid direct human exposure to high radiation levels and hazardous environments.

3.3.4. Maintenance equipment. With regard to maintenance equipment, the manual provides detailed information on the different maintenance means required. When the plant equipment requires transportation for replacement or repair, the transport means such as bridge cranes, forklifts or OMPs are analyzed and explained in section 4 of this article.

Based on the experience of LIPAc and other research installations at CIEMAT, the following workshops have been envisaged to support the preventive and corrective maintenance:

- The vacuum workshop is mainly devoted to providing maintenance of any component or element which works under vacuum conditions, which are mostly located in the accelerator system (AS). Its main functions comprise reception and check of new equipment (components, tubes, and other vacuum spares); cleaning and repair of components and spares which work under vacuum condition; design, experimental test, and calibration of new prototypes of vacuum elements required for the AS.
- The liquid metals workshop provides the maintenance means of the lithium loop and its components. The specific functions of this workshop are the reception and check of the equipment and spares of the lithium loop; cleaning and repair of components and spares of the lithium loop; design, experimental test, and calibration of new prototypes for the lithium loop; along with preparation of raw lithium to fill or refill the loop.
- The mechanical workshop provides support to any maintenance and inspection operation which requires machining and mechanical assembly. The functions of this workshop include the repair of components such as supporting structures, drilling and threading holes, flanges, vacuum chambers, and similar elements; and manufacture of specific mechanical components and spares needed for the facility.
- The metrology workshop is conceived as a measuring laboratory to support any maintenance and inspection operation which requires precise measurement, like test of manufactured components by the mechanical workshop, calibration of movable parts of cranes and remote handling equipment, and reception and check of new equipment or spares with strict dimensional requirements.
- The electricity and electronics workshop is devoted to providing support to maintenance and inspection of any electric and electronic component, including the radio-frequency system. This workshop is also conceived as a laboratory to test existing commercial components within the safety regulations adopted by IFMIF DONES.

The technical specifications of the equipment included in these workshops have been a matter of investigation in this project, and involved a detailed examination of each equipment, features, and operational and safety requirements. These specifications have been used as parameters to further define and design the main installations required in each workshop, like for example, the power supply, cooling water, air renovations, temperature and humidity, etc.

3.3.5. Maintenance staff. The maintenance manual of IFMIF DONES employs a categorization system for maintenance personnel based on several criteria, including the source of employment (in-house or outsourced personnel) and radiation exposure. The latter classifies staff as either Class A (workers who receive an effective dose greater than 6 mSv yr^{-1}, or an equivalent dose greater than 15 mSv yr^{-1} for the lens of the eye, or greater than 150 mSv yr^{-1} for the skin and extremities), Class B (workers who receive an effective dose greater than 1 mSv yr^{-1} but less than those of Class A workers), or non-exposed workers (who receive less than 1 mSv yr^{-1}). The Manual also categorizes personnel according to their area of specialization, such as mechanics, electricians, control and instrumentation technicians, remote handling, liquid metal, vacuum and compressed air technicians, etc.

A simplified diagram of the organization of maintenance personnel is shown in figure 9.

The maintenance manager bears ultimate responsibility for the implementation and management of the maintenance plan, reporting to the IFMIF DONES Facility Manager. The maintenance manager will be technically supported by the maintenance technical office, composed of experienced maintenance engineers responsible for the optimization of maintenance resources, the analysis of the data, the development of models, and other technical responsibilities. Also, the manager is supported by health physics staff, comprising certified health physics specialists with training in radiation protection. Furthermore, the decision making of the maintenance manager in relation to the management of the maintenance plan, among other high-level decisions such as outsourcing policy, etc., is assisted by the Maintenance Steering Committee, which is composed at least by one responsible person for each IFMIF DONES system, the safety manager, the radiation protection manager, and one responsible individual from each maintenance technical unit (mechanics, electricians, control and instrumentation, etc).

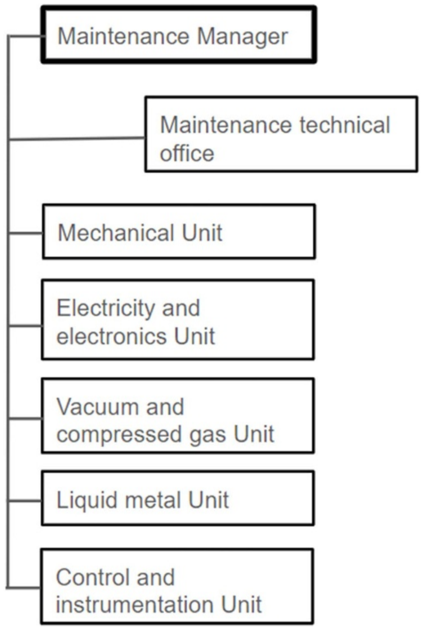

Figure 9. Diagram of maintenance personnel organization.

The second tier of responsibility falls upon the maintenance supervisors. These are a group of area-specific responsible persons whose main responsibility is to ensure that the personnel, resources and activities within their units are planned and performed in an optimized and safe manner, and also that the collaboration with outsourced personnel is well orchestrated. This requires constant coordination with their teams of technicians and with other supervisors to anticipate bottlenecks and identify needs (e.g. further outsourcing, a new spare part, etc) so that decisions can be escalated efficiently up to the maintenance manager. They are also supported by the maintenance technical office. Finally, the third tier corresponds to the area-specific technicians. They are responsible not only for the execution of the maintenance activities on site, but also for identifying anomalies and improvements needed both at the physical and organizational level.

3.3.6. Maintenance plan. Once IFMIF DONES facility is operating in stationary condition, there are two periods of forced downtime per year. There is a component in the accelerator that requires replacement twice a year (Boron Nitride disk) and there is a component in the lithium loop that requires replacement once a year (Target Assembly). We can then classify preventive maintenance operations according to the need of having some systems stopped or not:

- Preventive maintenance operations that can be executed regardless of the beam being on or off (Type 3 operations). Distributed along the whole year.
- After 171 d, replacement of boron nitride disk and other operations requiring beam off (Type 2 operations). Duration of this beam stop is 3 d.
- After 345 d, second replacement of boron nitride disk and replacement of target assembly, and other operations requiring beam off and flow of lithium stopped (Type 1 operations). Duration of this beam stop is 20 d.

The personnel, maintenance equipment and spares for these operations will be prepared well in advance, such that the downtime is minimized, and provisions for this purpose are included in the maintenance plan.

Even applying carefully designed preventive maintenance, some unexpected failure can happen, triggering the need of corrective maintenance. The maintenance plan includes documentation providing the guidelines for this corrective maintenance:

- The definition of a plant-level corrective intervention decision workflow, that allows decisions to be efficiently escalated to the responsible person who will decide and coordinate on the optimal schedule (e.g. immediate action or wait until next shutdown period), and the need for resources (technicians, spare parts, workshops, etc).
- The provisioning of enough spare parts so that unexpected waiting times and delays are reduced to an absolute minimum. In this context, the manual provides a spare parts management plan with guidelines on how spare parts need to be provisioned and inventoried, taking into account the criticality of the spares and the management of their obsolescence, especially those from prototypes and non-conventional equipment.

Finally, another important aspect which is also included is, the systematic review and updating of the maintenance plan. Initially, it is expected that the maintenance plan will be updated at least twice a year, immediately after each of the two planned beam stops. This updating process will be entirely data and information based, using a CMMS, which will systematically generate, collect, structure and analyze reliability and maintenance data.

3.4. Maintenance matrix

The collection of all the preventive maintenance operations in a single document, is of great help for the holistic view of the needs that the maintenance department must cover. A good example of the complexity derived from the mix of commercial equipment and scientific prototypes in the facility is pointed out in [9]. We addressed this issue by producing an excel file including 1246 maintenance operations known as maintenance matrix.

Arranz *et al* [4] provides a condensed description of the content of this maintenance matrix and gives an example of the information contained for a specific piece of equipment. In the current section, new information is provided beyond what was published in the cited reference, including greater detail and justification of the data included in the maintenance matrix. The results of the data analysis and a list of conclusions and lessons learned are also included.

Defining maintenance tasks for all equipment, even at the conceptual level, simultaneously with the plant design serves several objectives:

- Makes it possible to detect if there are maintenance operations that require a change in layout or the installation of new equipment. For example, the maintenance or replacement of activated equipment will require remote handling equipment, the installation of which may need reinforcements in the building structure.
- Ensures that it will be possible to comply with regulations concerning equipment maintenance promoting the necessary changes. For instance, the fire protection system is subject to a regulation that exhaustively dictates the inspections of elements and their frequency, which may be unfeasible if certain system elements are placed in rooms that have forbidden access at all times due to the radiation and contamination levels.
- Prepare the necessary infrastructure for maintenance, such as bridge cranes, battery charging stations for electrical equipment (e.g. electric forklifts), and storage for maintenance equipment and tools. It also allows for space estimates needed for spare parts storage.

3.4.1. Content of the maintenance matrix. The following paragraphs outline the main concepts included in the columns of the maintenance matrix and their justification, which may be helpful for readers who are planning a similar activity during the design of a large research facility.

Unique identification of the maintenance operation: a number is generated that contains the first three digits of the PBS, followed by another three digits as a sequential index. This way, we can quickly identify the system and subsystem for which the maintenance operation is defined, ensuring that all equipment in the plant is covered. Since some subsystems encompass complex assemblies, there is an additional column called 'Device,' which refers to the specific element of the subsystem to which the maintenance operation applies. Another column provides a description of the operation, clearly but concisely indicating what must be done, e.g. replacing the boron nitride disk. An additional column indicates whether this maintenance operation requires a spare part or not, depending on whether it involves a replacement or an inspection, for example.

Location of operation and maintenance of the 'Device': generally, maintenance activities are performed *in-situ* unless the equipment needs to be moved to a workshop. Along with the room where the maintenance is performed, the radiological classification is also indicated, which is relevant information to know whether the maintenance worker needs to be trained as a radiation-exposed worker, or if the operation needs to be done using remote handling equipment.

Required plant state: refers to the need of having the beam off or the lithium loop stopped for the execution of the maintenance operation, being classified as Type 1, 2 or 3 as explained in section 3.3.6.

Priority in analyzing the maintenance operation: when a new maintenance operation is included in the matrix, an evaluation is conducted using engineering criteria to assess whether it may require a modification to the building layout. For instance, if it requires the installation of a bridge crane with a large payload capacity, it must be analyzed as soon as possible to provide feedback to the building structure designers. All maintenance operations requiring remote handling equipment have the highest priority for detailed analysis due to the difficulty and cost of adapting the building later on.

Safety relevance: the safety importance class of SSCs is assigned based on the consequences that the loss of function could entail. The resources for maintenance are limited and consequently some information is required to prioritize which maintenance operations must be executed first. Given that, one key objective of maintenance is to maintain the level of radiological safety, the safety class of the device requiring a maintenance operation is the most important attribute to consider. This stands for preventive as well as for corrective maintenance. The safety importance class 1 (SIC-1) components should always get maximum priority.

Frequency, duration and number of people required: for each preventive maintenance operation, the frequency of the operation in times per year is assigned, sometimes obtained from the applicable regulation, or obtained from guidelines for that kind of equipment. For the elements of the accelerator, feedback from a similar facility (LIPAc) has been used. For commercial elements the handbooks of representative equipment were considered. The duration estimation and number of people required has been done mainly by using engineering judgment, this information would be very useful for the first estimate of the workforce required. Advice from the maintenance team of the Fusion National Laboratory (CIEMAT) was profusely used for these estimations.

Performer of the maintenance operation and training requirements: Some maintenance operations must be executed by external specialized companies according to applicable regulations (e.g. some Fire Protection System maintenance operations). For scientific prototypes, the performer should be an inhouse specialist. For access to some rooms, the education and qualification of workers exposed to radiation is a requirement, among other safety-related requirements. All this information related to demands on the people executing certain maintenance operations must be taken into account when defining the workforce for a maintenance campaign.

Predecessor and successor operations: some operations should be performed in a certain order and this information would be basic for the generation of the work orders in a certain sequence. For example, the checking of vacuum tightness in a sector of the accelerator should only be executed once all the elements of the beam chamber that needed replacement have been assembled again. The generation of this information is a daunting task and is not yet included in the current Maintenance Matrix, but this work must be done for the proper working of the CAMMS software once it is established.

It is noted that future versions of the maintenance matrix will include information about the isolation requirements for maintenance, especially for electrical and fluid connections,

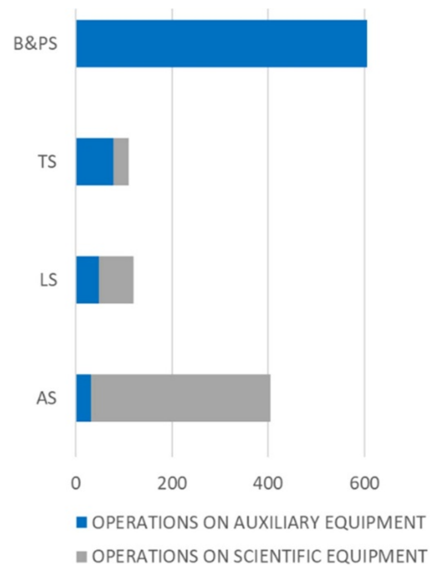

Figure 10. Distribution of number of operations depending on being executed on scientific or auxiliary equipment. Building and plant systems (B&PS), test systems (TS), lithium systems (LS) and accelerator systems (AS).

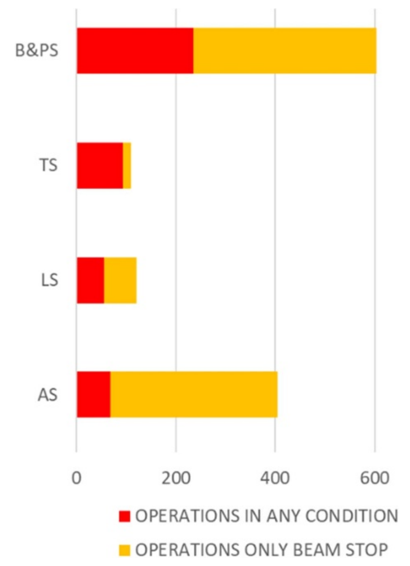

Figure 11. Distribution of number of operations that can be done in any condition and those that can only be done when the beam is stopped. Building and plant systems (B&PS), test systems (TS), lithium systems (LS) and accelerator systems (AS).

both prior to and during the execution of maintenance operations. This addition will help mitigate occupational risks associated with maintenance.

3.4.2. Results of the analysis of the maintenance matrix. The analysis of the data in the maintenance matrix can support the decisions made when defining the strategy for maintenance and the size and specialization of the workforce whether it is in-house or outsourced. Using the filters capacity of the spreadsheet, we obtained the data shown in figure 10. It can easily be deduced from the graph that the number of operations involving auxiliary or commercial equipment is larger than the number of operations applied on scientific equipment, the last may require a higher level of specialization and probably will be performed by in-house maintenance workers. The B&PSs are completely made up of commercial equipment hence all their maintenance operations can be easily outsourced. The TSs and lithium systems (LS) include both auxiliary commercial elements and some scientific equipment hence only part of the maintenance would be easily externalized. The accelerator systems (ASs) include a large number of scientific equipment therefore in this case, most of the maintenance operations should be assigned to in-house maintenance workers.

Some maintenance operations can be executed at any time, regardless of the beam of the accelerator being on or off, this is because the equipment is in a room where the level of radiation is low independently of the state of the machine (e.g. it is located outside of the main building). Some operations are simple inspections or can be executed on a component that is redundant and consequently is not in operation. We can observe in figure 11 that more than half of the operations have to be accommodated in the two planned periods of beam stop, but still there is a good number of maintenance operations (mainly on auxiliary equipment) that can be distributed along the year, balancing the workload of the maintenance crew.

3.4.3. Conclusions and lessons learnt while generating the maintenance matrix. While working on the compilation of information to complete the Maintenance Matrix, it would have been very helpful to create a model of the predetermined maintenance cycle. This would have helped to more quickly determine what information is relevant to realistically model the process.

Scientific equipment are often custom-made prototypes designed specifically for the plant in question, making it very difficult to obtain information on the maintenance operations that need to be applied to them. It is advisable that project management promotes exchange of information with research facilities with similar equipment.

The regulations and standards applicable to commercial equipment are crucial for defining which maintenance operations should be included. Therefore, it was essential to identify the Spanish national regulations applicable in this respect.

The parallel work of creating content for the maintenance matrix and designing equipment and systems often requires estimating values using engineering criteria. We recommend documenting the criteria used for these estimates. This will help to maintain consistency in the updates that may occur over consecutive years and could be carried out by different people.

In order to progressively introduce corrective maintenance information, FMECA analyses should be available so that the corrective maintenance with the highest likelihood of being necessary can be prioritized. It may be convenient to manage preventive and corrective maintenance separately, although they will logically share many common resources: maintenance workers, maintenance equipment and tools, and spare parts.

3.5. Maintenance policy future development

In order to unlock the full digitalization potential of the maintenance planning at IFMIF DONES, several research and development lines are being considered to allow the progressive implementation of a condition-based predictive maintenance approach. One promising research line in this context is the development of an advanced modeling tool for whole-system maintenance modeling enabling predictive maintenance planning and dynamic rescheduling of activities based on the current and anticipated condition of the assets. To this end, the integration of machine learning algorithms within state-of-art system representation techniques such as high level petri nets [28] or intelligent petri nets [29], among others, are being considered due to their transparency and their potential to capture the intricacies of complex processes such as the maintenance of IFMIF DONES. Moreover, another desirable future research line in this direction is the development of collaborative digital twins [30] covering the different aspects of the maintenance of IFMIF DONES. This development would enable the dynamic interaction between the maintenance workers and managers and their smart assistants using natural language and wearable technologies (smart watches, smart glasses, etc.), converting IFMIF DONES maintenance process into a transparent and deeply intelligent but human-centered expert system.

4. Logistics in IFMIF DONES

4.1. Previous works in logistics

The layout of the rooms where samples are irradiated and those where activated materials are handled is of utmost importance in a radiological facility. Back in 2012, an analysis from a logistical perspective was published regarding the IFMIF (International Fusion Material Irradiation) project during a phase preceding the current IFMIF DONES [15]. From this analysis, the proximity between the irradiation room and what is now known as the irradiated material treatment cells (IMTCs) was inherited. In the IMTC the irradiated samples are extracted and packaged in individual containers to be sent to the laboratories for testing. From [15] it is known that the distance between the IMTC and irradiation room shall be as small as possible. This short distance enables the use of a single transportation equipment which in turn means that no transfer between different transportation means is necessary thus increasing reliability. This single transportation equipment is a remote-handling telescopic crane which is especially designed for DONES with a very high reliability and in turn high cost.

In 2019, a methodology based on flowcharts was published to analyze the flow of materials within the main building of IFMIF DONES [3], considering the following factors: the path to be taken (in its different stages) and the means of transport. A manual analysis of the architectural drawings provided an estimate of the elements where clashes are expected (doors, corridors, freight elevators, airlocks).

From 2020 up to 2024, several tasks have been carried out to successfully overcome some of the logistics challenges: (1) defining optimal means of transport for equipment of very different sizes and weights, some of them radioactive, (2) establishing a methodology to efficiently update interference detection when the building or transported equipment characteristics change, (3) defining the criteria for using a shielding cask during the transport of activated equipment, (4) analyzing logistics alternatives for installation and commissioning, (5) analyzing and listing the equipment that must be transported and installed during the construction phase of the main building.

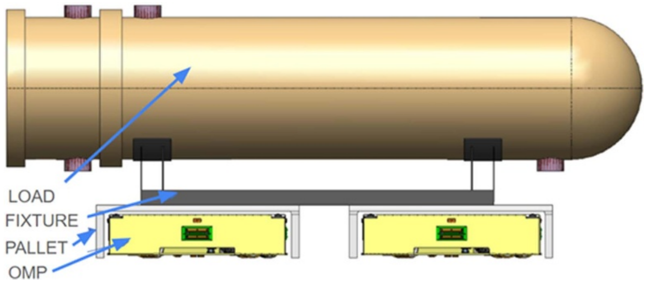

Figure 12. Heat exchanger being transported with two OMP modules.

Section 4.2 through 4.4 summarize the work related to transportation and installation of equipment in the main building mainly focused on issues that could require a modification in the building layout. Other topics of logistics such as spare parts management or transport of components to the site are not considered yet in our research.

4.2. Transportation means and concept

It was considered a priority to resolve the issue of transporting radioactive equipment within the main building, although the selected means of transport will also be able to transport non-radioactive and uncontaminated equipment. The requirements considered include: capacity to transport heavy equipment (up to 40 tons), electric motorization, teleoperation, omnidirectional movement, capability for rescue in case of failure, and radiation hardness. An analysis of the possible alternatives can be found in [31]. As a result of the research, an omnidirectional wheeled platform was recommended, capable of working in tandem, with each module having a load capacity of 20 tons.

A contract for the conceptual design was made with the company Solving, resulting in a proposal like the one shown in figure 12. The proposed system is based on what we call the OMP. Each unit can be placed underneath a pallet, which lifts the load by 40 mm using hydraulic cylinders before starting to move. The pallet has external dimensions of 2.7 m $\times$ 2.3 m $\times$ 0.7 m (length $\times$ width $\times$ height). A fixture, which serves as an interface with the transported equipment, can rest on a single pallet or on two, as shown in the figure.

Each OMP module has electric motors and a battery with a range of 3000 m of travel with maximum load. A 400 V, 16 A, 50 Hz battery charging system allows each OMP to be recharged while idle.

These OMPs are controlled from teleoperation controls that the maintenance worker uses while moving a few meters away.

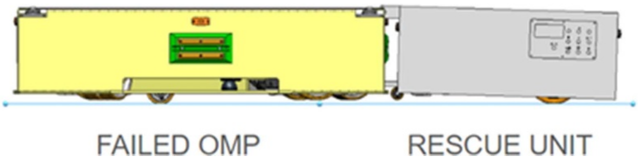

Figure 13. Rescue of a failed OMP.

They can also be teleoperated through a WLAN network, from a central control room, preventing the worker from having to be close to the load, in case it is radioactive. There are cameras distributed throughout the facility, in addition to OMP own onboard cameras to allow this teleoperation.

The maximum speed of this OMP is 0.3 m s^{-1} and they have flatness requirements on the surface on which they move, according to group 3 of the DIN 18202:2019 standard. On steps such as those that may appear at the access to a freight elevator, heights of up to 2.5 mm (vertical difference of surfaces) and gaps of up to 5 mm (horizontal distance between the floor of the building and the freight elevator platform) are permitted.

The rescue procedure can be seen in figure 13, using a rescue unit. If the OMP that failed was transporting cargo, the first operation would be to lower the pneumatic cylinders, so that it can come out from under the pallet. The rescue unit would attach to the failed OMP through an electrical connector and lower the free-spinning wheels. This rescue unit can be attached to the failed OMP on two of its orthogonal sides.

An alternative to the solution presented in the previous paragraphs is currently being developed, based on smaller OMP units. These are wheeled platforms from the company FORMIC [32], which also work in synchrony to transport large loads. In this case, three OMPs can be placed under a pallet (figure 14(*A*)), or four when two pallets are required (figure 14(*B*)).

The model C100 of FORMIC has a load capacity of 10 tons, and each unit can rotate on its own axis, in addition to performing linear movements. They have similar requirements and capabilities to those presented in the previous paragraphs, but their smaller size makes the rescue process easier.

The transport between different floors of the main building has also been studied in IFMIF DONES. Various alternatives available in the market were considered, and those that could meet the requirements were evaluated. Key requirements include those necessary for ensuring material flow, such as a minimum surface area, load capacity, a limit on acceptable vibrations, and notably, a reduced step at the access point from the building floor to the freight elevator. A detailed analysis can be found in [33], where it was concluded that only parallel ropes lifts and rigid chain lifts are viable. These results were provided as feedback to the building design team.

A systematic analysis of the transport and overall handling of all equipment within the IFMIF DONES site was also carried out. Based on the product breakdown structure of the project, the entire transport and handling cycle of each element

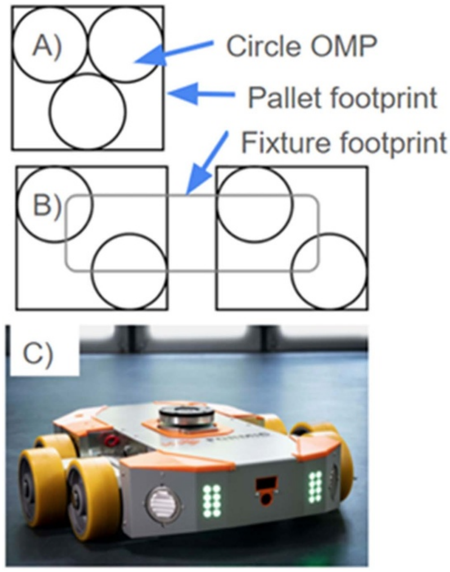

Figure 14. (*A*) Formic OMP units rotating on their own axis. (*B*) Two pallets supporting a fixture to transport a large piece of equipment. (*C*) Example of a Formic OMP.

has been reviewed. A series of assumptions were made: (1) new or replacement equipment is stored in a Warehouse, which is a separate building near the entrance to the site, (2) the new or replacement equipment is not activated and can therefore be transported to the main building entrance using conventional means, (3) within the main building, transportation will primarily be done via OMP, (4) used or failed equipment may or may not be radioactive, and its destination will vary accordingly.

For the installation or replacement of each piece of equipment, two transport stages have been considered: the first from the Warehouse to the entrance of the main building, and the second from the entrance of the main building to the room of installation. Transport between buildings, from the warehouse to the main building, is generally considered to be done using conventional trucks, while inside the main building, transport is mainly done using OMPs. In case the equipment is very small, a hand-cart alternative is considered.

When a piece of equipment needs to be removed because it is worn out or has failed, there is a new transport stage from the room of installation to one of the following three destinations: (1) IMTC, if it is radioactive, (2) Loading bay, if it is not radioactive, and (3) workshops, if it requires repair. This transport will generally be done using OMPs.

Before each transport, there is a handling task to load the equipment on the transport vehicle, and once at the destination, to unload it. For each piece of equipment, a handling method has been proposed, generally consisting of bridge cranes, mobile cranes, and electric forklifts.

The transport vehicles as well as the handling methods have been included in a spreadsheet for each piece of equipment to be transported. The selection has taken into account

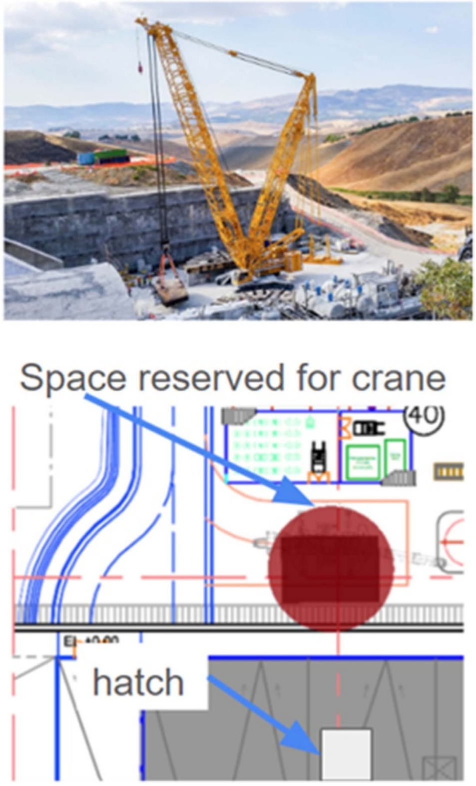

Figure 15. Top: image of the LIEBHERR LR 1500 crawler crane. Bottom: space allocated outside the main building and a hatch on the roof for equipment installation.

the following criteria: estimated frequency of the transport operation, dimensions of the transported equipment, weight of the transported equipment, radiation and contamination levels of the transported equipment, and the radiation and contamination levels of the room where the handling takes place.

Resulting from this analysis, a recommendation has been made for the rooms where it is deemed necessary or clearly advantageous to install fixed bridge cranes, which should be installed during the building construction phase and taken into account for the mechanical design of the structure.

A final concept for handling extremely heavy equipment is the use of crawler cranes. Specifically, the LIEBHERR LR 1500 model [34] has been proposed for the installation of equipment from outside the building, as shown in figure 15.

There are some extremely heavy elements that are not expected to be replaced during the lifetime of the facility, but in the event of an unforeseen failure, a planned method for doing so must exist. This is the case, for example, of a reinforced concrete slab used as radiation shielding over the vessel where irradiation takes place. This element, which we call the Upper Shielding Plug, weighs 120 tons, making the transportation through the corridors of the building unfeasible. A circular area has been reserved outside the main building, with a diameter of 19.2 m, where the crawler crane could be stationed as shown in figure 15. From there, a steel liner with welded reinforcement bars could be introduced into the room of installation, where concrete would later be pumped to construct the upper shielding plug *in situ*. Prior to the introduction of a new steel liner, the failed component will be cut in smaller pieces, transported to the IMTC and disposed of as solid radioactive waste. The hatch will only be opened once the old component is disposed of and no activated components are present in the Access Cell thus only contaminated air poses a threat to the environment which can be dealt with by mobile airlocks for example.

Something similar happens with the air handling units, which have dimensions of 3.55 m $\times$ 2.51 m $\times$ 6.89 m (width $\times$ height $\times$ length) and a weight of 11.4 tons. In this case, the dimensions prevent transportation inside the building, so once again, a crawler crane stationed outside will be used to introduce the equipment, but not through the hatch in this case. The installation room for these units has been strategically located on the outermost part of the building, so that the Air Handling Unit can be brought in through a lateral opening from outside.

4.3. Procedure for intralogistics analysis

The layout of the rooms in the main building and the sizes of doors, corridors, and airlocks were changing as systems progressed in their definition. Additionally, some equipment were only preliminary defined, and when detailed design is carried out, they sometimes have larger external dimensions. Both factors mean that the analysis of interferences in the transport of equipment inside the main building must be repeated periodically, specifically it has been conducted on an annual basis.

In addition to considering the external dimensions and weight of the equipment being transported, any necessary fixtures, the pallet, and the OMP must also be included. The combination of all these elements is referred to as the total transport unit, and it is the envelope of this unit that we use to check for any interferences. The dimensions and weight of each piece of equipment are recorded in an Excel sheet, which is reviewed by the system coordinators to update the necessary data. This file is considered the source of truth for exchanging this information. Additionally, the file includes the coordinates of the origin and destination, as well as whether the equipment can be rotated for transport.

The transport attributes of each piece of equipment and the building layout are the input data for the Anylogic software, which, after performing the corresponding analyses, identifies clashes between the Total Transport Unit and doors, airlocks, and other architectural elements. These results are discussed with the building and equipment designers to make the necessary modifications. This procedure is described in more detail in [35]. The use of Anylogic software is also applied in logistical studies for other fusion research facilities [13].

During the past year, additional structural restrictions were prompted and have been incorporated into the intralogistics analysis, particularly the maximum load per unit of surface area. On the one hand, there is a local load limit due to concrete cracking, set at 10 000 kN m^{-2}. This is calculated as the load of the total transport unit divided by the footprint of the wheels on the ground. This is not an issue for the transported elements. However, there is an average load limit to maintain structural

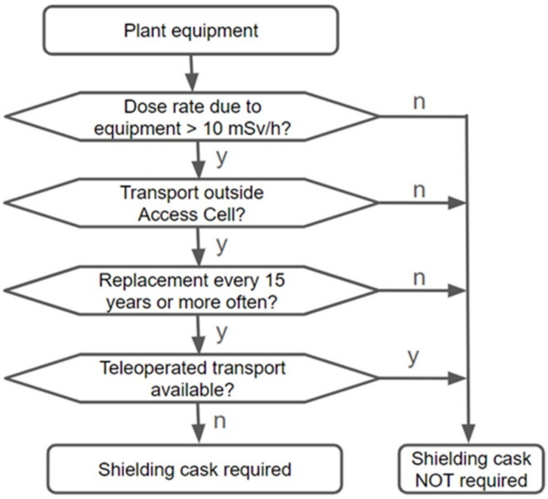

Figure 16. Flowchart for decision on the need of shielding cask.

stability. This average load is calculated as the weight of the total transport unit divided by its footprint area, with a maximum allowable value of 25 kN m^{-2}. This limit is slightly exceeded in the transport of two types of elements: shielding elements and the heat exchanger shown in figure 12, for which individual studies will need to be conducted. In the case of the shielding elements, the solution could be to transport the liner and reinforcement bars separately and then pump the concrete once they reach the installation room. For the heat exchanger, it can be transported in two parts: the casing on one side and the tubes assembly on the other, with the final assembly taking place in the installation room. Another option is to reinforce the building structure along the path through which these elements are transported.

A factor of utmost importance when planning the transport of activated and contaminated elements is the need to use shielding casks. In IFMIF DONES, a flowchart has been created, which appears in figure 16. The proposed dose value (10 mSv h^{-1} at 1 m distance) is inspired by the IAEA publication 'Regulations for the Safe Transport of Radioactive Material.' It should be noted that the ALARA principle will be applied, which in this case is implemented by using a shielding cask, even if the flowchart does not require it, as long as its use does not entail a change in the structure of the building. Additionally, any activated and contaminated equipment will be packaged in a sealed bag or container to prevent the spread of contamination during transport.

If the transport is carried out in the room known as the access cell, only remote handling cranes will be used, so a shielding cask is not necessary. If a piece of equipment is scheduled for replacement in periods of more than 15 year, this means it will be replaced at most once during the lifetime of the facility, which is designed to operate for 30 year, and therefore a specific analysis will be realized for that case. If teleoperated transport equipment such as OMP is available, the vehicle can be controlled from a central control room without the need for workers to be near the activated equipment, so biological shielding is not essential.

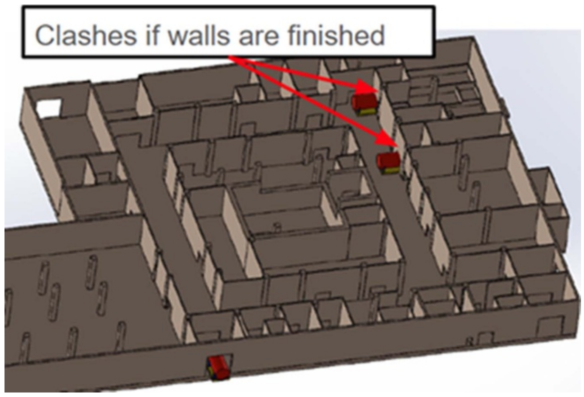

Figure 17. Clashes in the transport of liquid radioactive waste treatment system tanks with doors of airlocks.

When radioactive equipment is transported without a shielding cask through the main building, all rooms in the vicinity of the transport path will be evacuated to avoid absorbed doses by workers.

4.4. Logistics for first installation and commissioning phase

Section 4.2 explained the planned inclusion of a hatch in the roof of the building to address unforeseen failures of certain components in the irradiation area (Test Cell). However, the initial installation of these components will be more efficient if carried out during the construction phase.

A systematic analysis has been conducted for this type of components that do not have a periodic replacement and, due to its size and weight, should be installed during the construction phase of the main building. The following paragraphs explain the factors considered in this analysis and the results obtained.

All the fixed bridge cranes in the facility have small clearances relative to the walls supporting the rails on which they move. Additionally, the girders and trolley are heavy elements, making them ideal candidates for installation on the corresponding floor before the ceiling is constructed.

There are two tanks in the liquid radioactive waste treatment system that are 5 m high and 2.8 m in diameter. They will be transported in a horizontal position, on an OMP, using a pallet and a fixture. This creates interferences with the doors of the airlock leading to their installation room (see figure 17). The proposed solution is to transport them before erecting the walls on which the airlock doors will be mounted. If a failure in the tanks requires its replacement, a modular design would be used in that case avoiding the need of knocking down walls.

The air handling Units mentioned in section 4.2 should also be installed before the exterior of the building enclosure is completed, once the floor slab of the level on which they rest is capable of supporting the load.

Lastly, the vessel where irradiation takes place (TC liner) has dimensions of approximately 8 m wide, 8 m long, and 11 m high. The concrete shielding slabs that cover it are also of such large dimensions hence transporting them through the corridors of the facility is not feasible. Therefore, one of the walls of the room where the vessel will be installed must remain open until these elements have been brought in using a crawler crane.

Another activity carried out in the logistics area has been the evaluation of various alternative commissioning plans for the accelerator. Some plans required the transport of heavy radioactive components, such as the beam dump, which weighs around 50 tons (but can be split in smaller parts), with its central element, which stops the accelerated particles, becoming radioactive during the start up phase. The currently selected plan consists of four phases [36], with the beam dump being transported at the end of phase two. The challenges posed by this transport are due to its heavy weight, as mentioned before, but also its radioactivity. The logistics analysis contributed to choosing the optimal commissioning plan.

4.5. Conclusions of the logistics tasks

The logistics analysis activity has been carried out simultaneously with the design of both the building and the plant equipment, providing the necessary feedback to ensure that transport is feasible. A modular transport system within the main building has been proposed, and the handling methods for loading and unloading at each stage have been defined. The cases of exceptionally large and heavy equipment have been analyzed, both for their initial installation and for their eventual replacement. A flowchart has been developed to determine which equipment should be transported using a shielding cask. In summary, a comprehensive research and support effort has been developed for the overall design of the facility.

The trend in logistics investigation for fusion research plants is to automate the generation of inputs [37], as well as the modeling, analysis, and the generation of transportation proposals [38], in the same vein, our aim is to reduce the manual steps in the logistics analysis for the IFMIF DONES project.

5. Conclusions and future work

The analysis of logistics and maintenance processes during the design phase of the building and plant equipment has been very helpful in providing feedback and avoiding future problems during installation and periods of inspection and replacement of parts.

The VR tools have been fruitful in detecting inconsistencies in the designs of equipment and support structures. Feedback has also been provided to the designers of remote handling equipment and transport containers, leading to modifications of their initial designs. Additionally, the virtual visits tool has been used for discussing the layout of air conditioning and gas ducts within the project itself, and as a means of dissemination with VR headsets for people outside the project. Potential future developments could include the visualization of dose rates and the accounting of accumulated dose in the mannequin representing a maintenance worker. It would also be useful to implement augmented reality and, finally, the automatic generation of movements for the actuated equipment.

The tasks carried out in defining the maintenance policy have targeted compliance with Spanish regulations and standards for radioactive facilities. All predetermined maintenance tasks have also been defined, which will allow for the development of a resource optimization model based on Petri nets. In the future, the gradual introduction of predictive maintenance is planned.

Regarding the results of the tasks associated with logistics and transportation, it can be assured that the means of transporting spare parts are viable since the dimensions of architectural elements have been modified to avoid collisions. A fleet of OMPs, cranes, and other means such as electric forklifts and portable cranes have been proposed, making the initial installation and the replacement of all plant equipment feasible. Future activities in this area include a study on resource allocation to effectively carry out the necessary transports during predetermined maintenance.

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