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ideas

Inizio, questa pagina dedicata ai ringraziamenti, dicendo che non avrei mai immaginato di poter frequentare la scuola di Dottorato in Ingegneria dei Sistemi Meccanici. Non potrei continuare a scrivere se innanzitutto non ringraziassi l'amico Prof. Giuseppe di Gironimo per aver creduto in me. Penso che il nostro paese abbia fortemente bisogno di uomini che mettano in condizione i giovani di esprimersi al meglio delle loro possibilità, dando loro un'opportunità così com'è accaduto a me. Voglio inoltre ringraziare il prezioso, amico, Andrea Tarallo, per il supporto in tutte le attività insieme sviluppate e l'estemporaneo, amico, Stefano Papa.

Dedico il presente lavoro a mia moglie, Maria, e ai miei figli Anna e Mario…

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Chapter 1 *Introduction and Acknowledgements*

1.1 Introduction

Virtual Reality (VR) can be defined the technology improving the interaction between human and product models, adding perception with visual, tactile, sound realistic sensations in a real-time simulated environment, [1]. It is a simulation technology that allows the designers to interact with the digital model of the product, before it has been physically realized, [1, 2, 3].

Currently VR techniques are well developed in the scientific research field, but their massive application in industrial contexts is still a challenge. The main objective of the present work is developing a methodology able to integrate VR engineering tools in the industrial contexts.

The possible benefits of VR are becoming more visible to industry users, moreover the current state of Virtual Reality guarantees their implementation with low investment costs. In the last years the research and development on the VR reality tools has made great strides forward. Nowadays we can find on the technological market simple low cost solutions of VR reality tools. In this context the implementation of VR tools in the industrial contexts can become interesting also in terms of returns of the investment costs in VR. For this reason the present works focused on developing a methodology to implement the VR tools in industries field. The methodology developed has been tested not only on research applications but mainly on industrial project and real products.

Digital Mock-Up (DMU) and numerical methods, such as FEM or CFD analyses, have become very common in industrial design (*Virtual Product Development*). However, the full integration of these analyses with other aspects mainly related to the *context of use* of the product and its life cycle (e.g., ergonomics, maintainability, usability, etc.) is still quite a challenge for designers. Furthermore, with the increasing complexity of industrial products, critical evaluation of these aspects needs very specialized skills that may not belong to a single individual, but instead they are shared among the entire production system, which is increasingly being distributed internationally. This means that design review activities must include a two-way horizontal information flow on the project, capable of interfacing skills that would otherwise be distant from each other.

Moreover, although many software applications help designers to draw-up product technical documentation and to perform maintainability analyses, methods to summarize all the information coming from these analyses are needed.

1.2 Acknowledgements

I wish to thanks for precious collaboration:

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- ✓ **Eurofusion Programme Management Unit: Max-Planck-Institut für Plasmaphysik, Garching,Germany**

- ✓ **VTT Technical Research Centre Tampere Finland**

- ✓ **Laer Aeronautical Manufacturing Airola Italy**

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Chapter 2 *Materials and Methods*

2.1 Introduction

To date the VR engineering tools are well developed but their implementation and integration in industrial contexts is still a challenge. The main requirement of the methodology is the capability to integrate the VR engineering tools in industrial contexts. In order to implement the methodology structure the product lifecycle has been divided in different phases, for each phase the most suitable VR engineering tool has been defined. In detail the work has been divided in four main steps:

- definition of the product ***lifecycle phases***
- identification of the ***needs*** for each product lifecycle phase
- definition of the most appropriate ***VR tool*** for each phase, capable to fill the needs
- testing of the VR tools on real projects and in real industrial contexts

In the next paragraphs will be described in detail each step.

2.2 Product lifecycle phases

In scientific literature we can find a lot of definitions of the product lifecycle phases. For example John Stark in his book "*Product Lifecycle Management*" claims that there are five phases in a product lifecycle (Figure 2.1). In each phases, the product and its design are in different state.

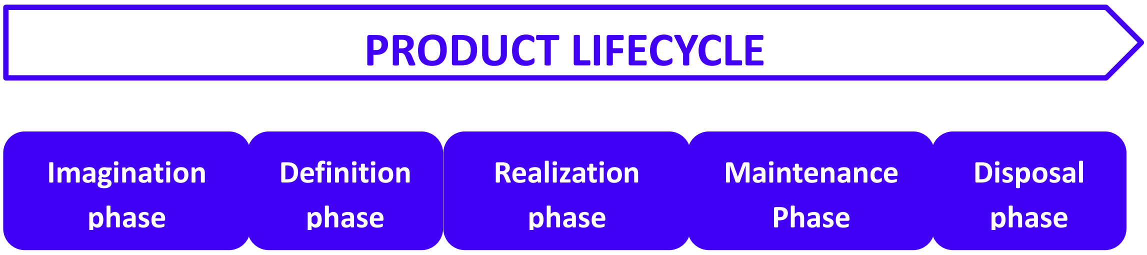

Figure 2.1 Product Life cycle phases according to Stark definition

During the imagination phase, the product is just an idea in people's heads. During the definition phase, the ideas are being converted into a detailed description. By the end of the realisation phase, the product exists in its final form in which it can be used by customers. Eventually the product gets to a phase in which it's no longer useful. It' is retired by the company, and disposed by the customer. The product must be managed in all these phases to make sure that everything works well, and the product makes good money for the company. That means managing the product throughout its lifecycle, "from cradle to grave".

Three of the lifecycle phases (Imagination, Definition and Realisation) make up the beginning of the product. There is a middle of life phase which includes activities such as product use, support and maintenance. There is an end of life phase which includes activities such as product retirement, disposal and recycling [1].

Starting from the Stark product lifecycle definition we focused our studies on the first four phases. These phases, subsequently, have been divided in (Figure 2.2):

- *Conceptual Design Phase*
- *Preliminary Design Phase*
- *Design Validation Phase*
- *Detailed Design Phase*
- *Product Engineering and Production Phase*
- *Maintenance Management Phase*

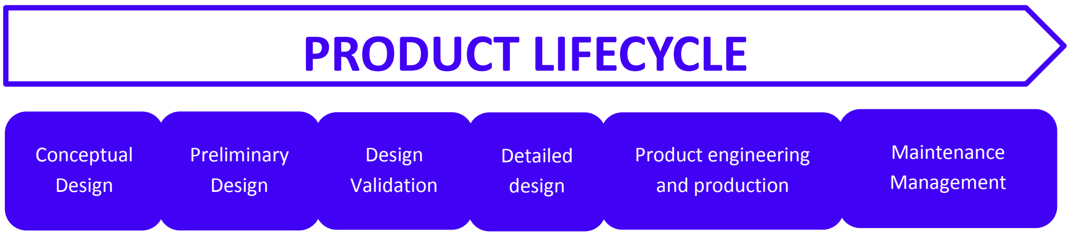

Figure 2.2 Product lifecycle phases

Different organizations may undertake different stages in the life cycle. However, each stage is conducted by the organization responsible for that stage with due consideration of the available information on life cycle plans and decisions made in preceding stages. Similarly, the organization responsible for that stage records the decisions made and records the assumptions regarding subsequent stages in the life cycle [3].

2.2.1. *Conceptual Design Phase*

The Concept Stage is executed to assess new business opportunities and to develop preliminary system requirements and a feasible design solution. During the Concept Stage, the design teams begin in-depth studies that evaluate multiple candidate concepts and eventually provide a substantiated justification for the system concept that is selected[2]. The definition of the product requirements based on customer, company, market and regulatory bodies' viewpoints is made in this phase. From this specification, the product's major technical parameters can be defined. In parallel, the initial concept design work is performed defining the aesthetics of the product together with its main functional aspects.

In some concepts, the investment of resources into research or analysis-of-options may be included in the conception phase – e.g. bringing the technology to a level of maturity sufficient to move to the next phase. However, life-cycle engineering is iterative. It is always possible that something doesn't work well in any phase enough to back up into a prior phase – perhaps all the way back to conception or research. There are many examples to draw from.

2.2.2. *Preliminary design phase*

In this phase the product requirement and the main assumptions are identified. All design team involved in the project starting their design activities. The conceptual ideas, outcomes of the previous phase, became drawing and schemes. Each design team taking into account the requirements defined in the conceptual design turn in drawings and schemes the first design choices.

2.2.3. *Design validation phase*

The Design validation phase is executed to develop a system-of-interest that meets acquirer requirements and can be produced, tested, evaluated, operated, supported, and retired [2].

This stage includes development, and integration, verification and validation activities. Figure 2.3 illustrates the evolving baseline as system components are integrated and verified.

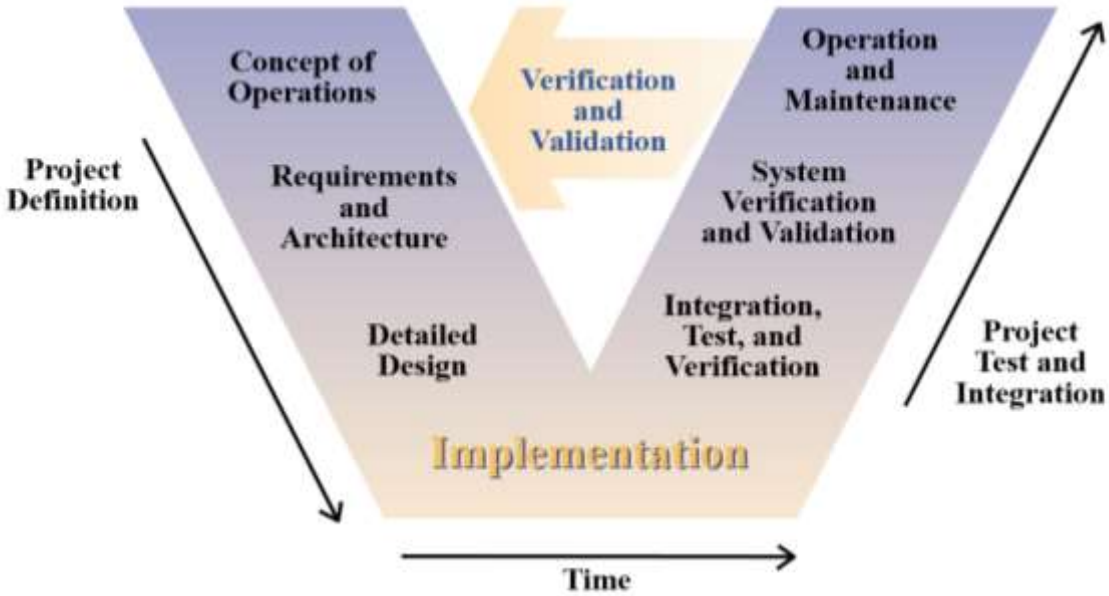

Figure 2.3 Vee model [4]

Moreover this phase avoids all problems related to interference design choices, outcomes from the preliminary design of the different teams involved in the project.

2.2.4. *Detailed design phase*

In this phase the detailed design and development of the product starts, progressing to prototype testing, through pilot release to full product launch. It can also involve redesign and ramp for improvement to existing products as well as planned obsolescence. This step covers many engineering disciplines including: mechanical, electrical, electronic, software, and domain-specific, such as architectural, aerospace, automotive.

2.2.5. *Product engineering and production phase*

The Production Stage is executed to produce or manufacture the product, to test the product, and to produce related supporting and enabling systems as needed. Product modifications may be required to resolve production problems, to reduce production costs, or to enhance product or system-of-interest capabilities. Any of these may influence system requirements, and may require system re-verification or revalidation. All such changes require systems engineering assessment before changes are approved [2].

2.3 Maintenance management phase

The Support Stage is executed to provide logistics, maintenance, and support services that enable continued system-of-interest operation and a sustainable service. Modifications may be proposed to resolve supportability problems, to reduce operational costs, or to extend the life of a system. These changes require systems engineering assessment to avoid loss of system capabilities while under operation. The corresponding technical process is the Maintenance Process [2].

2.4 Needs and Virtual Engineering Tools adopted

Starting from the definition of the product lifecycle phases, for each of it's the main needs have been defined. Moreover depending on the needs an appropriate VR engineering tool has been chosen.

2.4.1. *Needs and tools in conceptual design*

In the *conceptual design* the main need consisted on manage few and confused ideas. Generally in this stage of product development heterogeneous design teams with heterogeneous background interact together. For this reason the main objective of this phase was developing a common platform to manage and integrate the information between the design teams.

2.4.2. *Needs and VR tools in preliminary design*

The typical analyses made in the *preliminary design* phase are the feasibility analyses. In order to perform these analyses the design teams needs of adequate tools capable to represent the overall project, summarizing the information outcome from each design team. For this reason the Immersive VR tool was used to make the feasibility analyses. These tools are capable to visualize the total project in an immersive environment.

2.4.3. *Needs and VR tools in design validation phase*

In the *design validation stage* the preliminary project of the product is completed, during this phase the main needs consist in analysis of project in order to highlight any interference in preliminary design choices. For this phase the VR engineering tools chosen were the robotic and kinematic simulation. Using these tools both validation and functionality analyses can be performed.

2.4.4. *Needs and VR tools in detailed design*

In the *detailed design phase* all design team provide all the detailed information about the final product. In the case of manufacturing industry, it is necessary evaluate the interaction between the product and human, frequently on the market we can find some products on which this aspect was not well evaluated. In order to satisfy this need, VR tool capable to perform ergonomic analyses has been adopted.

2.4.5. *Needs and VR tools in product engineering and production*

The success of a product is assured not only by his own quality but also by the efficiency of his manufacturing or assembly process. For this reason, the efficiency of the product manufacturing process has become a strategic aspect in the industrial field, in particular in the companies where the workers are the main driver of the production process. The VR tool chosen to satisfy this need is a digital human model capable to simulate, already in the design phase, the product assembly process and evaluate the interaction between the human and the manufacturing processes.

2.4.6. *Needs and tools in maintenance management*

The last phase considered in our product lifecycle definition consist in the management of the product manitenance, in particular in the optimization of the maintenance management system. For instance, referring to aeronautic industry, many authors have shown that the 45% of maintenance time is spent in reading technical documentation [6], [7]. Thus, several attempts exist in the published literature to develop new modalities for administering technical documentation. The VR engineering tools can supply to this need through interactive multimedia manuals that can guarantees usability of the maintenance information in the industrial contexts.

The Figure 2.4 summarizes the main structure of the methodolgy developed, for each product lifecycle phase both the needs and the appropritate VR engineering tool are defined.

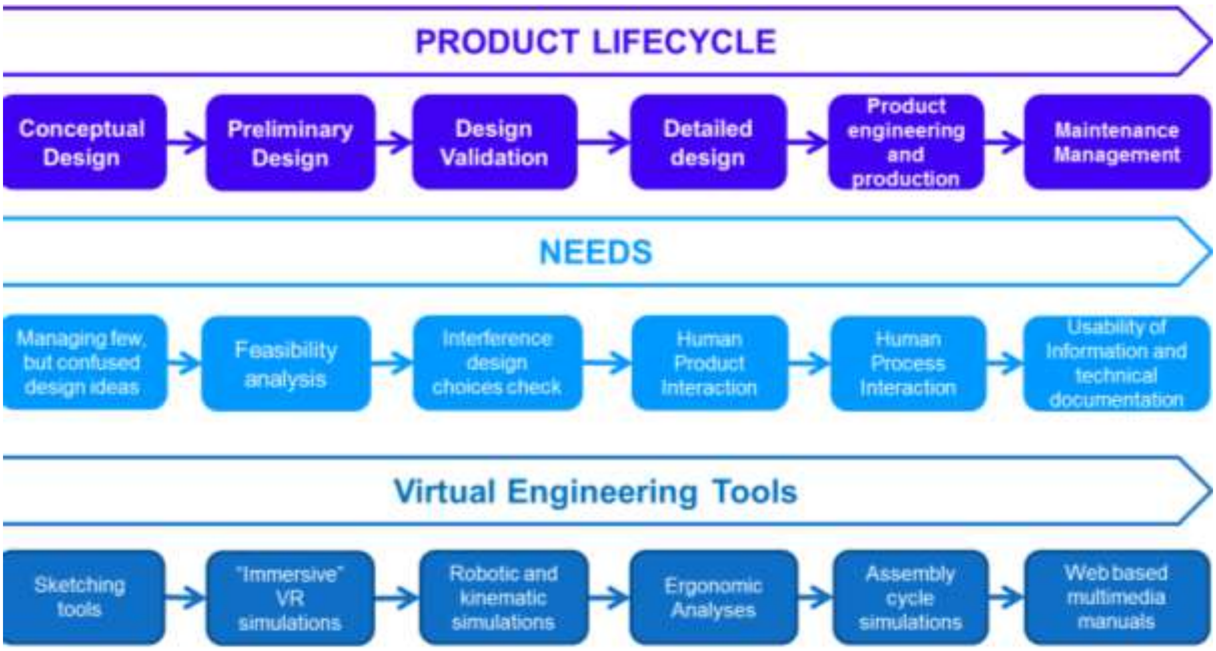

Figure 2.4 Methodology Developed

2.5 Testing of the methodology in industrial contexts

In the next chapters will be described the industrial applications in which the methodology was tested, in particular, for each product lifecycle phase an industrial application has been provided and tested. It should be noted that all applications have been developed in industrial contexts and on real products. Following the industrial application are summarized for each phase:

- ✓ Demonstration Fusion Power Reactor (DEMO) Vacuum Vessel **Conceptual Design;**
- ✓ **Preliminary** piping layout and integration of European Test Blanket Modules subsystems in International Thermonuclear Experimental Reactor (ITER);
- ✓ **Design Validation** of International Fusion Materials Irradiation Facility (IFMIF) remote maintenance tools;
- ✓ **Detailed design** of Bombardier C-198 Dorsal Fairing Jigs;
- ✓ Definition of the Bombardier C-198 Dorsal Fairing **assembly procedures**;
- ✓ ***Web Based Multimedia Manual*** of Local Train

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Chapter 3 *Industrial application: Demonstration Fusion Power Reactor (DEMO) conceptual design*

3.1 Introduction

In this application the VR sketching tools have been used to guarantees the exchange of information between three different design teams. This activity was developed in collaboration with Eurofusion Programme Management Unit Max-Planck-Institut für Plasmaphysik in Garching, Germany (Germany), VTT Technical Research Centre in TAMPERE (Finland) and ENEA Research Centre of Frascati (Italy). In detail Eurofusion PMU provided the first conceptual design of DEMO Vacuum Vessel (VV), VTT made a preliminary assessment on the DEMO VV taking into account aspects related to the remote maintenance of the DEMO divertor cassettes (DC) and ENEA performed the first structural assessment of DEMO VV. The aforementioned activities and the interactions between the design teams will be described in the next paragraphs. Sketching VR tools have been used at this stage of DEMO design to support the design teams in the information exchange.

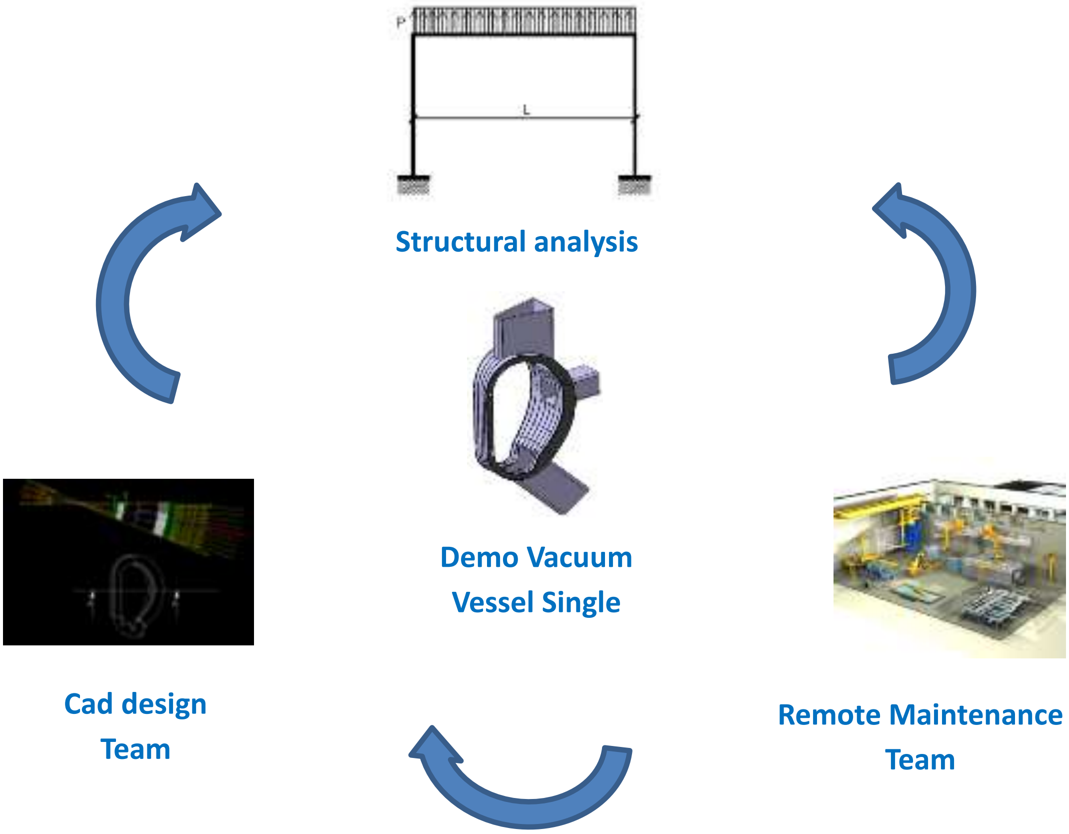

Figure 3.1 Interaction between DEMO design teams

3.2 Overview on the Demonstration Fusion Power Reactor DEMO

One important objective of the EU fusion roadmap Horizon 2020 is to lay the foundation of a Demonstration Fusion Power Reactor (DEMO) to follow ITER, with the capability of generating several 100 MW of net electricity to the grid and operating with a closed fuel-cycle by 2050. This is currently viewed by many of the nations engaged in the construction of ITER as the remaining crucial step towards the exploitation of fusion power. [1]

With the construction of ITER well underway, attention is now turning to the design of a successor device; a Demonstration Fusion Power Plant (DEMO), the nearest-term reactor design capable of producing electricity, operating with a closed fuel-cycle and to be the single step between ITER and a commercial reactor. Currently, no conceptual design exists for DEMO and work carried out in the past in Europe on fusion reactor design focused on the assessment of the safety, environmental and socioeconomic aspects of fusion power and less on rigorous technology feasibility assessments. [2]

3.3 Conceptual design of DEMO Vacuum Vessel

This activity concerns development of the 3d model of the DEMO Vacuum Vessel (VV). In the following paragraphs will be described:

- Quick check Analysis (QCA) to define the maximum distance between ribs and their layout in such a way the DEMO VV can withstand the operating coolant pressure;
- 3d CAD Modelling of the DEMO VV starting from QCA results.

The aim of the study was to develop a 3d model of the DEMO VV structure, useful and easily manageable to the next design phases such as FEM (Finite Element Method) analyses and Remote Handling assessment.

3.3.1. *Quick check analysis*

In order to estimate the maximum distance between the ribs and, therefore, their number a Quick Check Analysis (QCA) has been carried out. The analysis has evaluated the maximum bending stresses on the shell due to coolant pressure. The coolant pressure proposed is 3.15 MPA at 200°C [5]. Depending on the maximum stress obtained, it has been defined the maximum distance between the ribs and their number for each sector. In the following table are summarized the QCA input data.

Table 3.1 Input data Quick Check Analysis

Coolant Pressure	3.15 MPa
Static Scheme	Over constrained beam
Membrane stress limit (S_m)	130 MPA
Shell Thickness	60 mm
Standard Ribs Thickness	40 mm
Operating Temperature	200°C
Material	AISI 316 L (N)

According to [12], the primary membrane plus bending stress intensity shall not exceed 1,5*S_m :

$$\boldsymbol{P_m + P_b \leq 1,5S_m} \quad (1)$$

where P_m is the primary membrane stress and P_b is the primary bending stress.

The material considered is AISI 316 L (N) (Table 3.1), its yield strength at 200°C is [13]:

$$\boldsymbol{S_m = 130\ MPa} \ (2)$$

The reference scheme is an over constrained beam (Figure 3.2); the structure is loaded with the coolant pressure (Table 3.1).

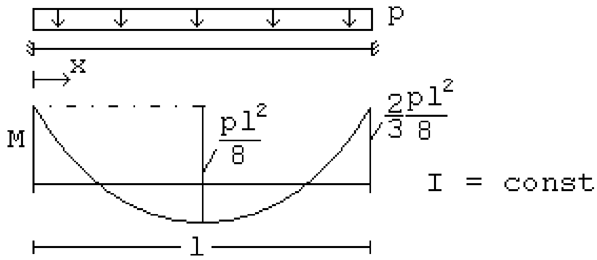

Figure 3.2 static scheme

The maximum bending moment on the shell due to coolant pressure is (Table 3.2):

$$\boldsymbol{M = \frac{qL^2}{12}} \quad (3)$$

$$q = pB \quad (4)$$

Figure 3.3 Bending moment diagram on the shell due to coolant pressure

The maximum allowable bending stress at the ribs is given by the following formula:

$$P_{bmax} = \frac{M}{W_f} = \frac{\frac{pBL^2}{12}}{\frac{Bh^3}{12}}\frac{h}{2} = 1.5\,S_m = 195\ MPa \quad (5)$$

The maximum allowable distance between two ribs on the equatorial plane is:

$$L = h\sqrt{\frac{2P_{bmax}}{p}} = 667\ mm \quad (6)$$

3.3.2. *3d CAD modelling of single sector of DEMO Vacuum Vessel*

Starting [1]from the guidelines contained in [4], the information contained in [3] and [5] and 3d cad reference model provided by PMU (Project Management Unit) [10], the layout and the number of the poloidal ribs was defined.

The layout of the ribs and shell, both at inboard and outboard, has been provided taking into account maximum allowable distance between ribs (667 mm) outcome of the QCA.

The software used in 3d cad modelling activities was CATIA V5 by Dassault Systemes. The model provided is a surface model, each component is modelled as a surface placed on the its mid-plane. This choice contributes to reduce time spent in geometry meshing activities during the FEM analyses.

3.3.3. *Modelling of Main Vessel Structure*

Eleven ribs have been placed on the outboard while five ribs on the inboard (**Figure 3.4**). Ribs are as near as possible to the center line of the five Breeding Blanket Sectors, as well as requested in the task guidelines [4](Figure 3.4).

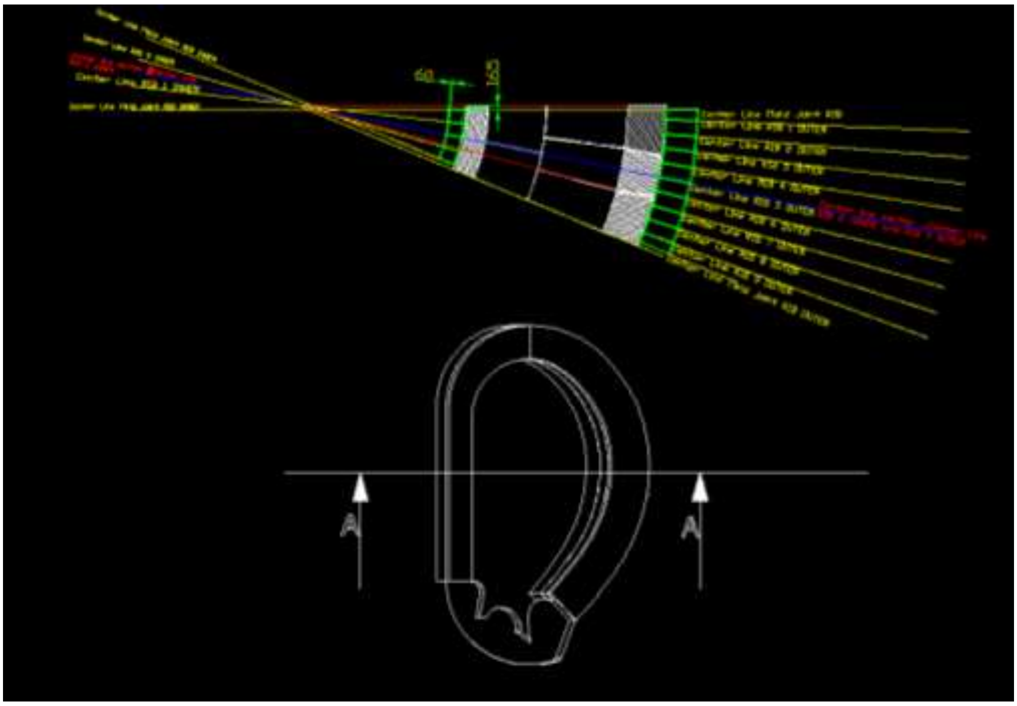

Figure 3.4 Ribs and shell layout of DEMO single sector

All ribs are symmetrical to the center line of the sector (i.e. the blue line in Figure 3.4). One rib is located on the center line of the sector both on the inboard and the outboard.

As requested in the guidelines [4], both on the inboard and the outboard two ribs are placed on the sides of sector and their center line is set 165 mm off the center line of the sector field joint (Figure 3.4).

The ribs profiles are obtained by intersection between the inner/outer vacuum vessel surfaces (Figure 3.5) and the ribs reference planes (center line of the ribs Figure 3.4). The ribs and shells layout analysis defined datum planes and angles on which the ribs had to be placed.

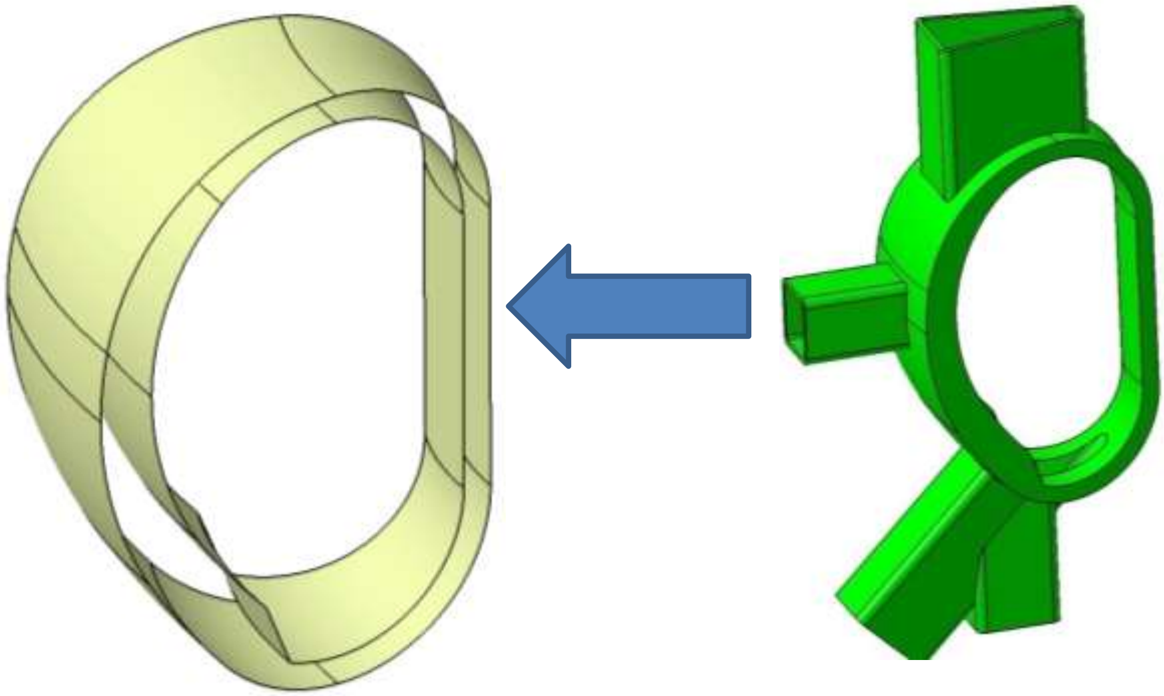

Figure 3.5 Inner and outer reference Surfaces

Therefore, using profiles of two adjacent ribs, single-curved shells have been modelled with 60mm thickness. In particular, all shells have a single curvature in poloidal direction (Figure 3.6), except at the inboard, where inner and outer surfaces of central segment are cylindrical and have a single curvature in toroidal direction (Figure 3.7). This choice guarantees a reduction of the shell manufacturing costs with respect to the shell double curved.

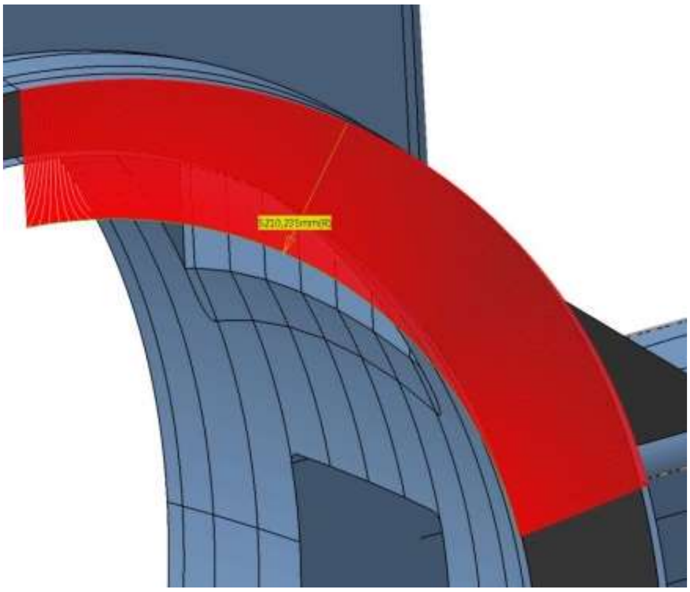

Figure 3.6 Curvature analysis of outer shell

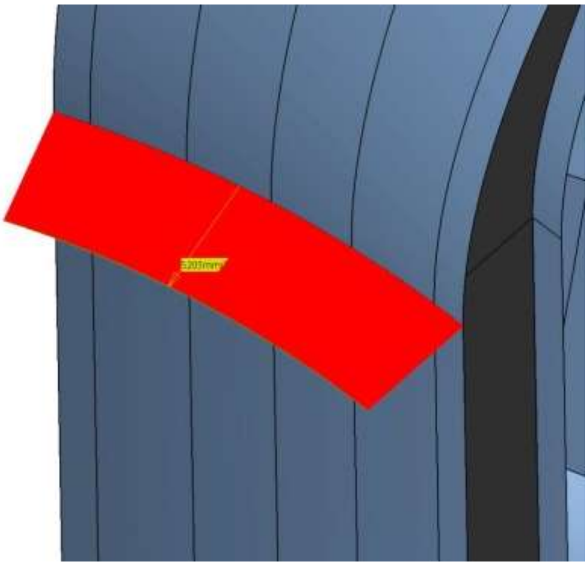

Figure 3.7 Curvature analysis of an inboard segment inner shell

All ribs have 40 mm thickness except in the case of the poloidal ribs number 2,3,7,8 (Figure 3.4). Their thickness is 80mm. These ribs are in line and joined with central and lower port gussets. This choice guarantees that loads can be transferred between the ports and the main vessel (highlighted in red in Figure 3.8).

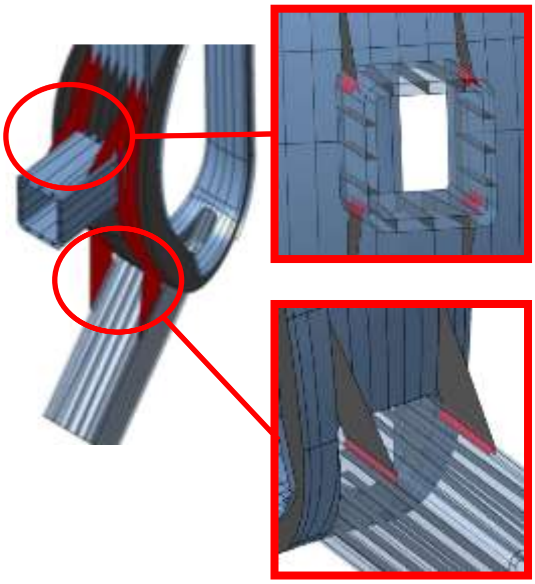

Figure 3.8 Gussets in line with poloidal ribs number 2,3,7,8

In detail the gussets are aligned to the poloidal ribs on the one hand and on the other hand are joined with the sidewalls of the ports through two short ribs (Figure 3.8). The thickness of gussets is 100 mm. The short ribs (Figure 3.9) have same behaviour of a machined component. In Figure 3.9 is shown shell model of the joint and Figure 3.10 illustrates model of the machined component.

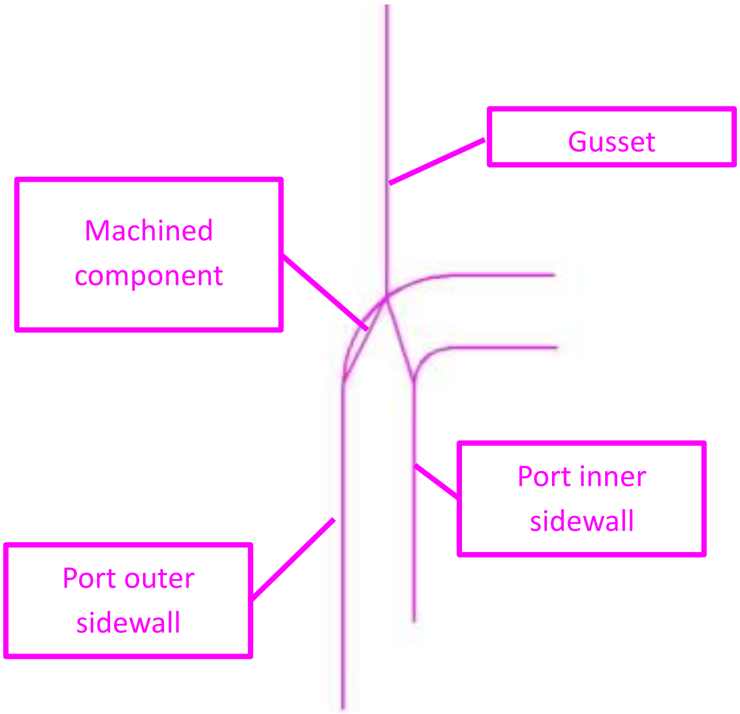

Figure 3.9 Shell model of the joint between gussets and ports

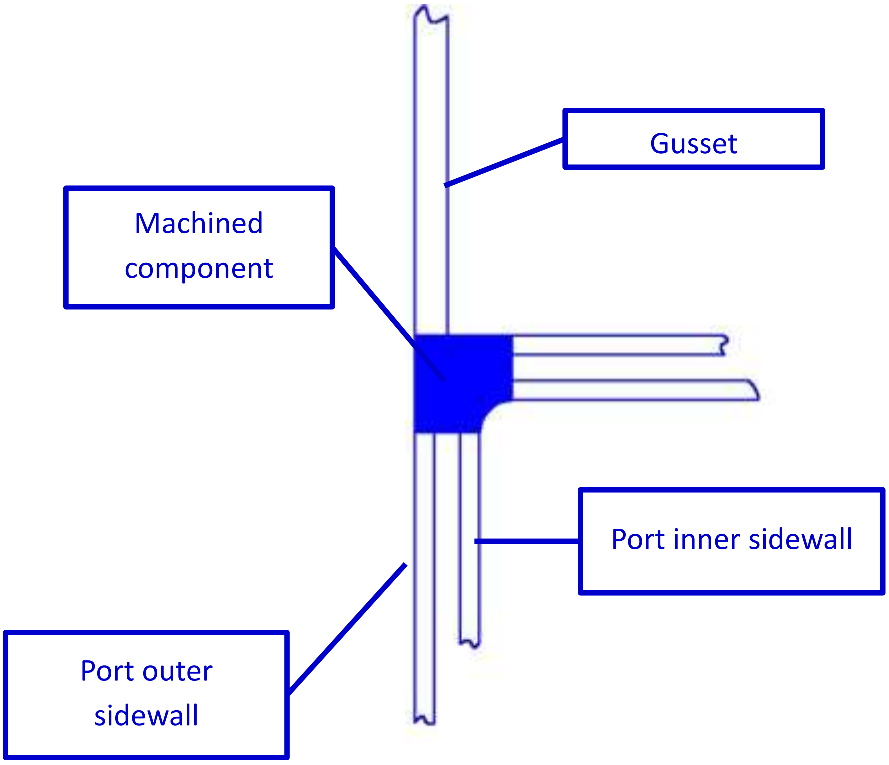

Figure 3.10 3d model of the joint between gussets and ports

The gussets with short ribs (**Figure 3.8**) assure a structural continuity between the main structure of the vessel and the ports. Load can flow from the poloidal ribs to the ports structures through the gussets and vice-versa.

In order to have distance between ribs less than 667mm, four short poloidal ribs have been added at the top and bottom of the inboard segment (highlighted in red in Figure 3.11). These ribs are joined together through one toroidal rib. Also in this case the poloidal ribs at the inboard are aligned with the poloidal ribs at the outboard.

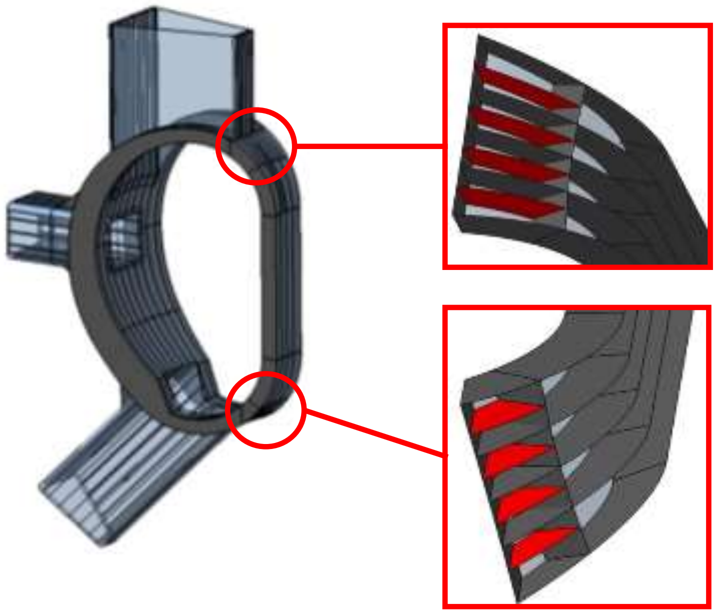

Figure 3.11 Poloidal ribs on the inboard segment

3.3.4. *Modelling of Upper Port Structure*

Upper port sidewalls are single walled and welded to both inner and outer shell, while at the inboard and the outboard the port has the same structure of the VV with ribs and shells (Figure 3.12). The port ribs are aligned to the ribs of the VV and are parallel to the axis of the port. This ensures a structural continuity between the upper port and the main vessel. It should be noted that also in this case the maximum distance between the ribs is less than 667mm.

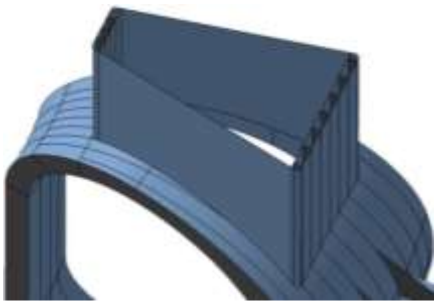

Figure 3.12 Upper port isometric top view

One toroidal rib has been placed on the top and aligned with the outer shell of the upper port (highlighted in red in Figure 3.13).

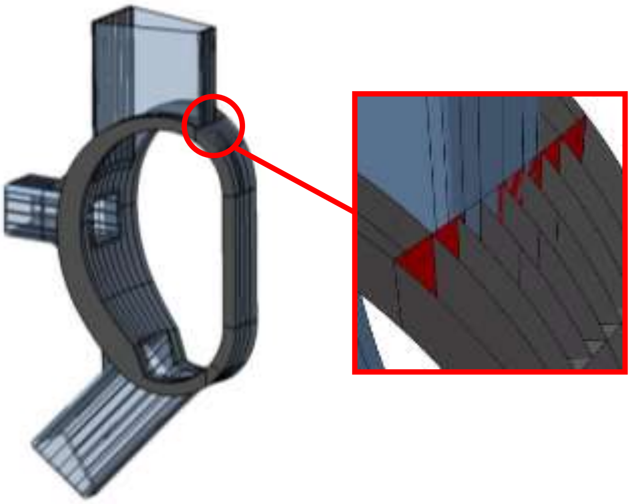

Figure 3.13 Toroidal rib aligned with the outer shell of the upper port

3.3.5. *Modelling of Central Port Structure*

The central port has been modelled using a double walled structure with ribs and shells. In particular 3 ribs have been placed on each side of the central port. The ribs on the top and bottom side are aligned with the ribs of the VV, while ribs on the right and left side of the port are parallel to the vessel equatorial plane (Figure 3.14).

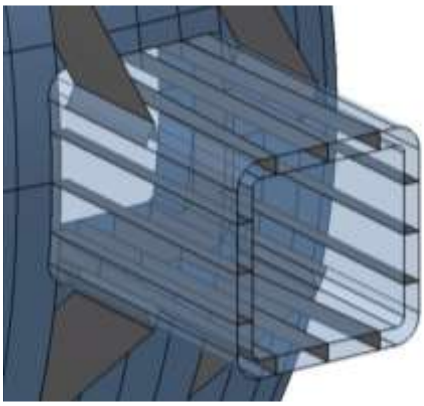

Figure 3.14 3d model of the central port

3.3.6. *Modelling of Central Port Structure*

Also the lower port has been modelled using a double walled structure with ribs and shells (Figure 3.15). The ribs placed on the sides of the port are perpendicular to the inner and outer shell and parallel to each other. On the top and bottom the ribs are aligned with VV ribs.

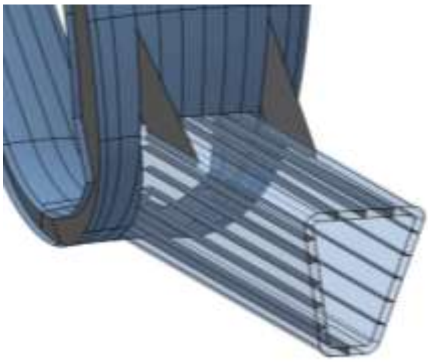

Figure 3.15 3d model of lower port

At the current stage DEMO VV supports have just been sketched to provide a coherent model to import in structural analyses. Each support is joined to the correspondent port sidewall (Figure 3.16).

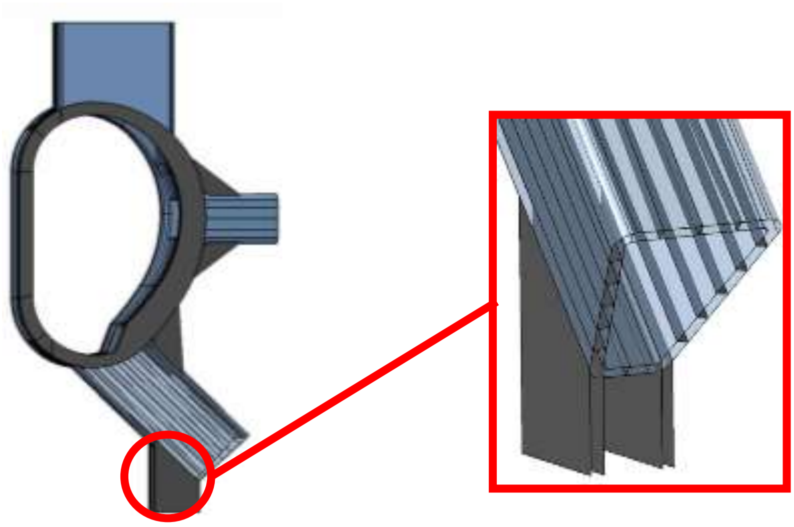

Figure 3.16 Supports on the lower port jointed to the four port sidewalls

As aforementioned the PMU design team has been provided the 3d sketched surface model of DEMO single sector starting from data of the QCA and the task guidelines of DEMO structural design. Each structural component is modelled as a surface placed on its mid-plane. This choice in order to prepare a 3d model on which to run the first FEM analyses using shell element type and to assess the divertor cassette remote maintenance.

3.4 DEMO Divertor Cassette Remote Maintenance Assessment

This activity concern a preliminary assessment on the DEMO divertor cassette (DC) remote maintenance considering as starting point the outcomes of the VV conceptual design. The activity was developed in collaboration with VTT (Tampere).

The inclination of the lower port of DEMO VV has a very important impact on all the remote handling tasks. The design of the divertor mover, the principle of the locking system, the end effector can be different depending on this parameter.

The reference current scenario foresees a 45° inclined port (outcomes of conceptual design of the PMU) for the remote maintenance of the DC in the lower area of the reactor. Nevertheless, in the optic of the System Engineering [16] approach in this early design phase, all the possible geometrical configurations shall be taken into account. Therefore, starting from the current scenario of the 45° port, other solutions have been studied and analysed from the RH point of view.

In this preliminary study it is possible to consider therefore, different options which have different impact on the current design of the Tokamak. These solutions even if not feasible in the early stage of the project need to be investigated and analysed , because they could lead to new engineering and technical proposal.

The analyses have been approached using a preliminary bounding box of the DC (Figure 3.17), in order to have a very first configuration of the size and space available in the VV.

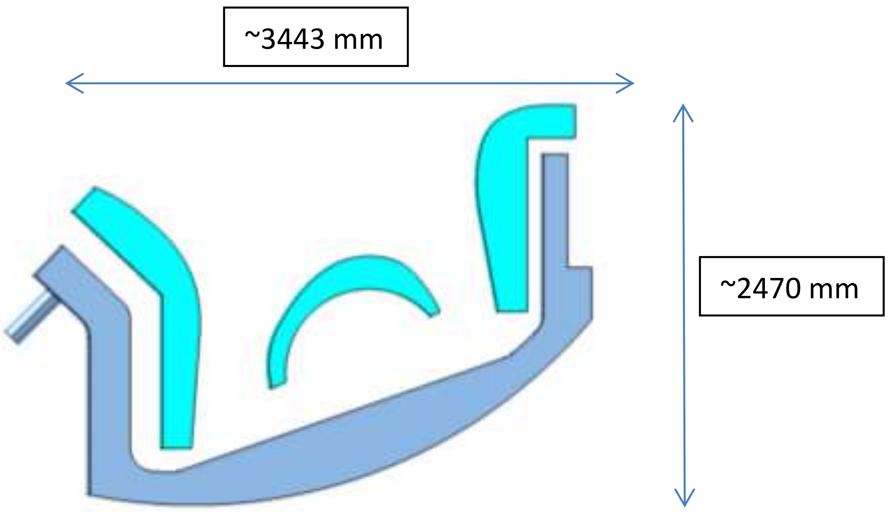

Figure 3.17 ITER scaled divertor cassette

3.4.1. *45° Port*

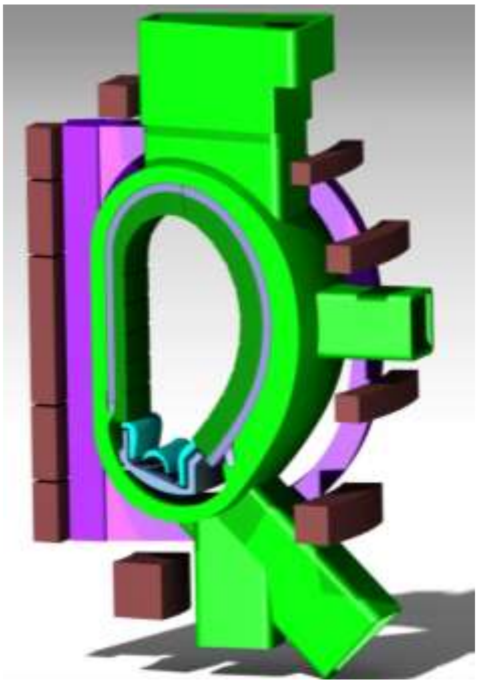

Figure 3.18 - DEMO 45° divertor port

The reference model of DEMO reactor is shown in Figure 3.18.
The maintenance port for the remote handling operation of the DC is inclined of 45°. The main advantage of this solution could be the independence of the remote handling operations between blankets and DC. Moreover, in this configuration the DCs can be driven inside (and outside) the vessel following a straight path. The DC can keep the same orientation from initial position to the installation and vice versa with no need of any rotation by the DC mover system.
One sequence of the removal of the central cassette is shown in Figure 3.19.This configuration is also suitable for the current position of the poloidal and toroidal field coils and the current profile of the port Figure 3.20.

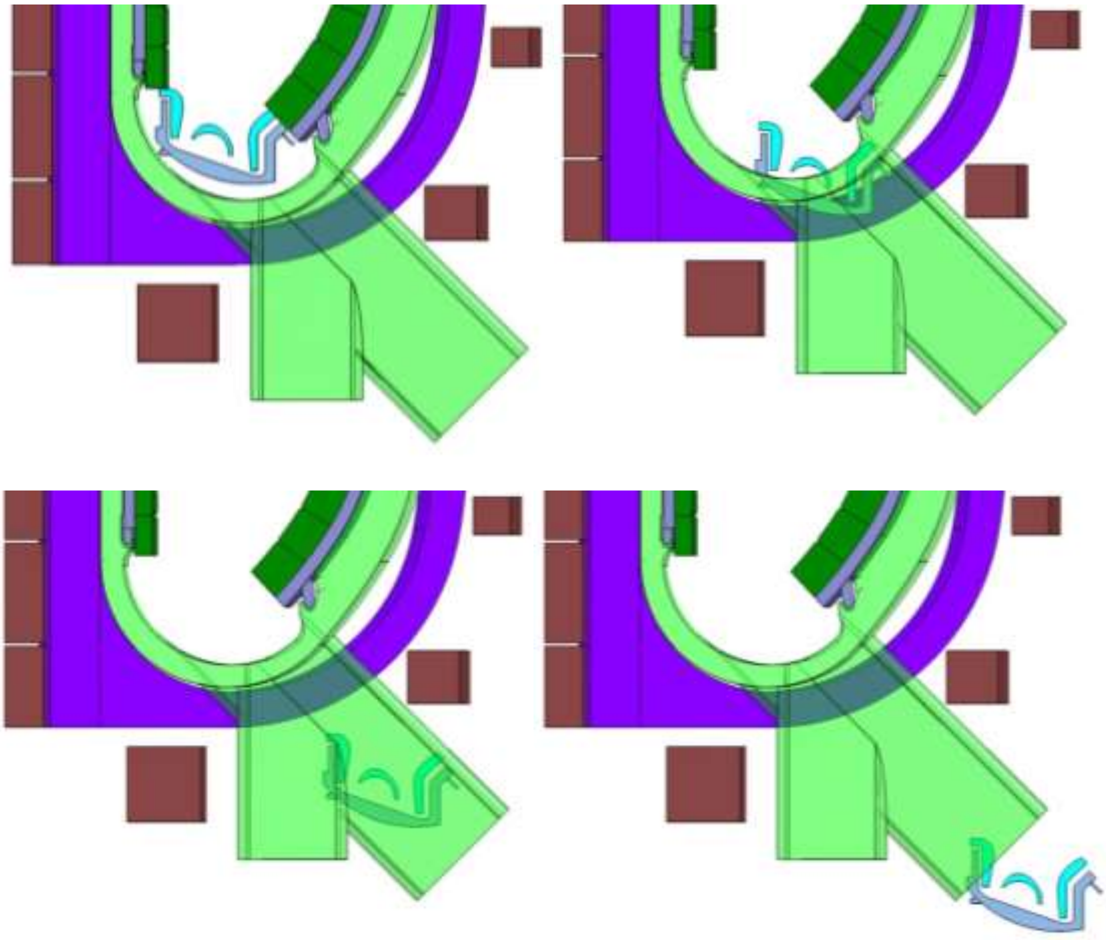

Figure 3.19 - C*entral cassette with 45° divertor port removal sequence*

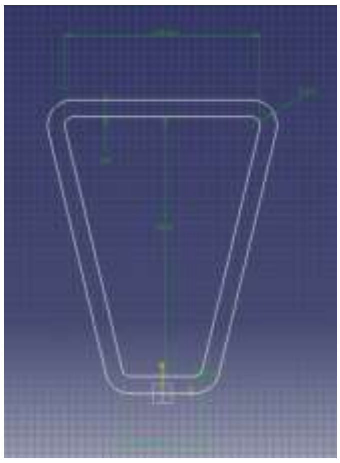

Figure 3.20 - Divertor port current profile

3.4.2. ***Horizontal Port***

The second scenario considered in this analysis is the configuration of the reactor with horizontal port for the maintenance of the DC, Figure 3.21.

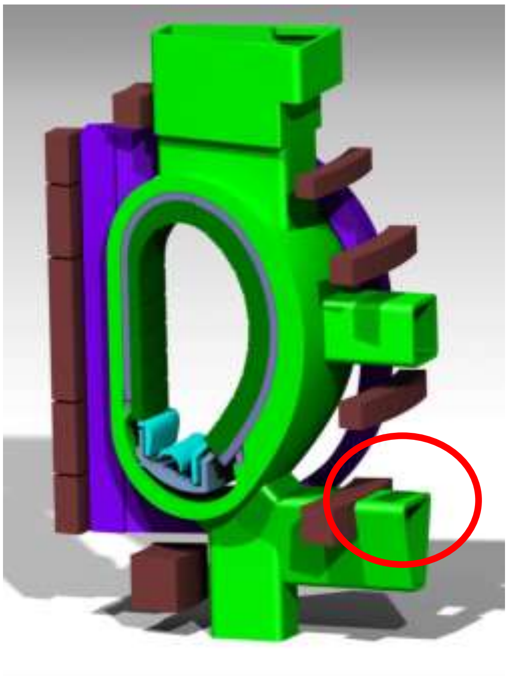

Figure 3.21 - DEMO Horizontal divertor port

The horizontal configuration has an incompatibility with the current position of the TF coils [17]. Nevertheless, this position has not been fixed yet. Therefore, if the horizontal configuration could result the best option in RH point of view, studies on the possibility to update and adapt the position of the coils are needed.

In order not to effect the current design of the blanket and its remote handling system, the connection of the port and the vessel is inclined 45° (Figure 3.22)

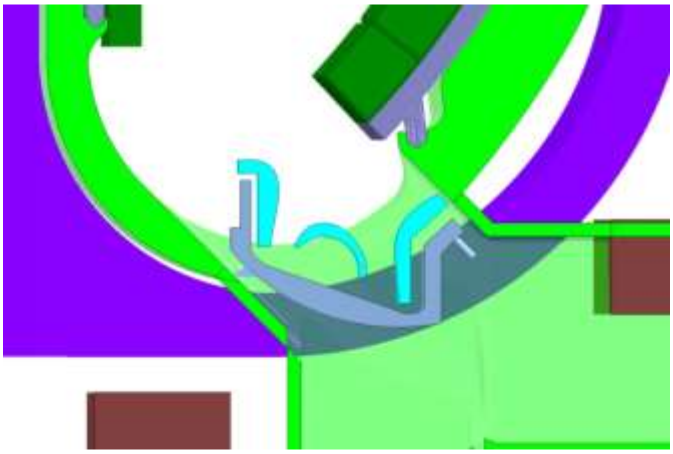

Figure 3.22 - Horizontal port-Vacuum Vessel connection

Therefore, in this configuration, during the movement of the DC, it is assumed that the DC mover shall be able to drive the DC straight in the horizontal part of the tunnel and then the lift it in the VV. The sequence of the operations is shown in Figure 3.23.

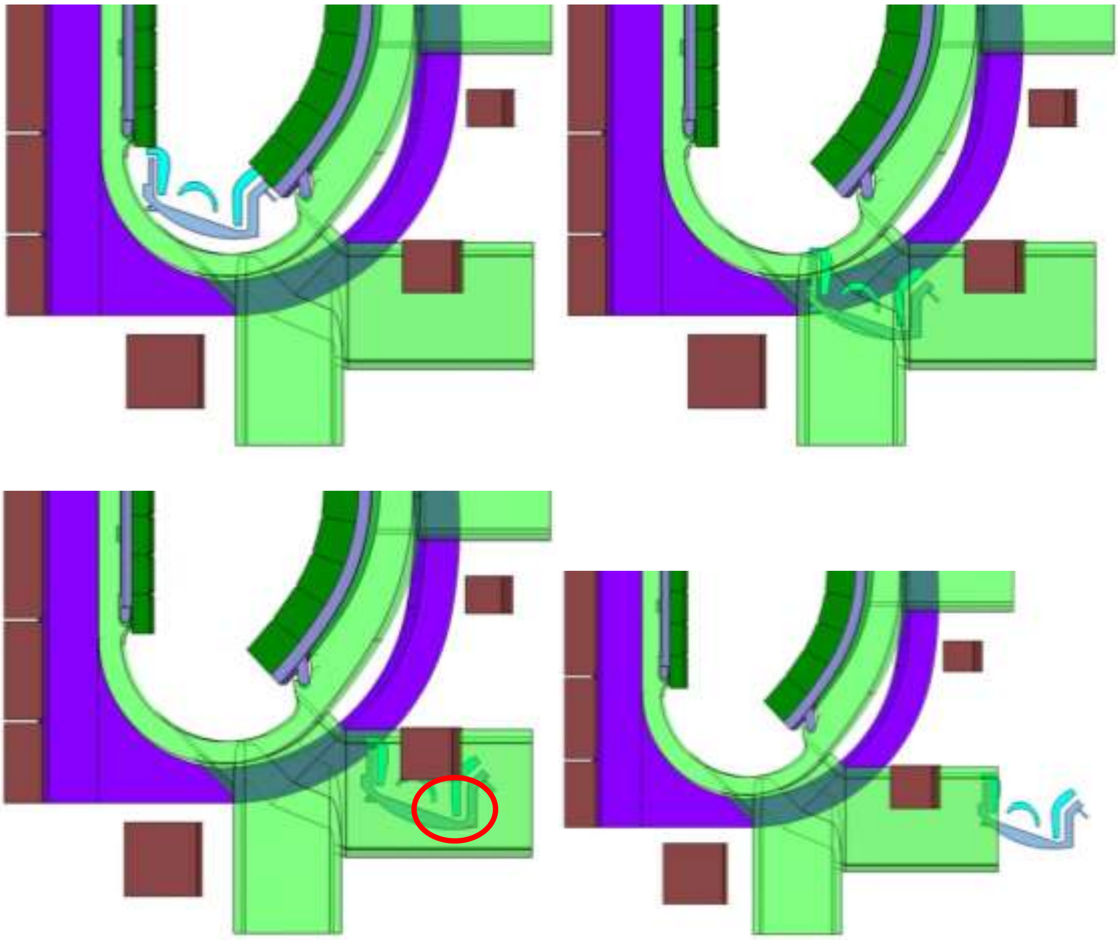

Figure 3.23 - Divertor cassette removal sequence in the horizontal port

As highlighted, the orientation of the DC cannot be the same during the entire operation because of the interferences with the current profile of the port. Two are the possible actions. Modify the size of the port or rotate of a minimum of 5° the DC and lowered it of about 200 mm, in order to avoid any collision with the port, as shown in the sequence in Figure 3.24.

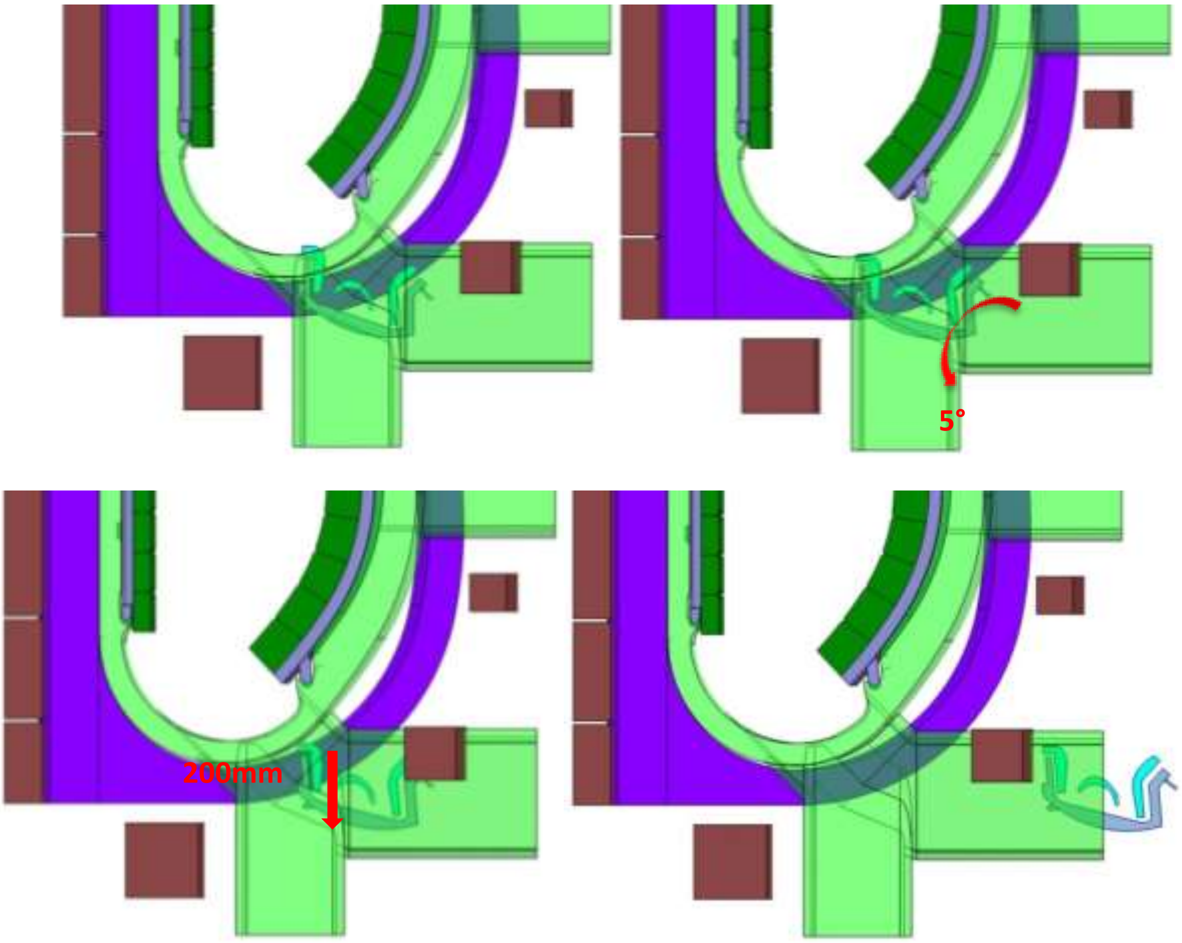

Figure 3.24 - Proposed divertor removal sequence in the horizontal port

As consequence of these first studies and kinematic analysis, in this configuration the DC mover shall be able to rotate and move in the vertical direction the DC.

3.4.3. *Hybrid Port*

A third case-study has been the combination of the 45° and horizontal port, Figure 3.25.

Figure 3.25 - DEMO divertor hybrid port (45° + horizontal)

This configuration does not need any changes in the current position of the magnetic coils. The kinematic sequence is shown in Figure 3.26 . In this configuration, the DC shall be rotated of about 10° in order to avoid collision with the upper ceiling of the lower port (Figure 3.26 and Figure 3.27). As a consequence, the DC mover shall be able to rotate the DC, together with the horizontal translation.

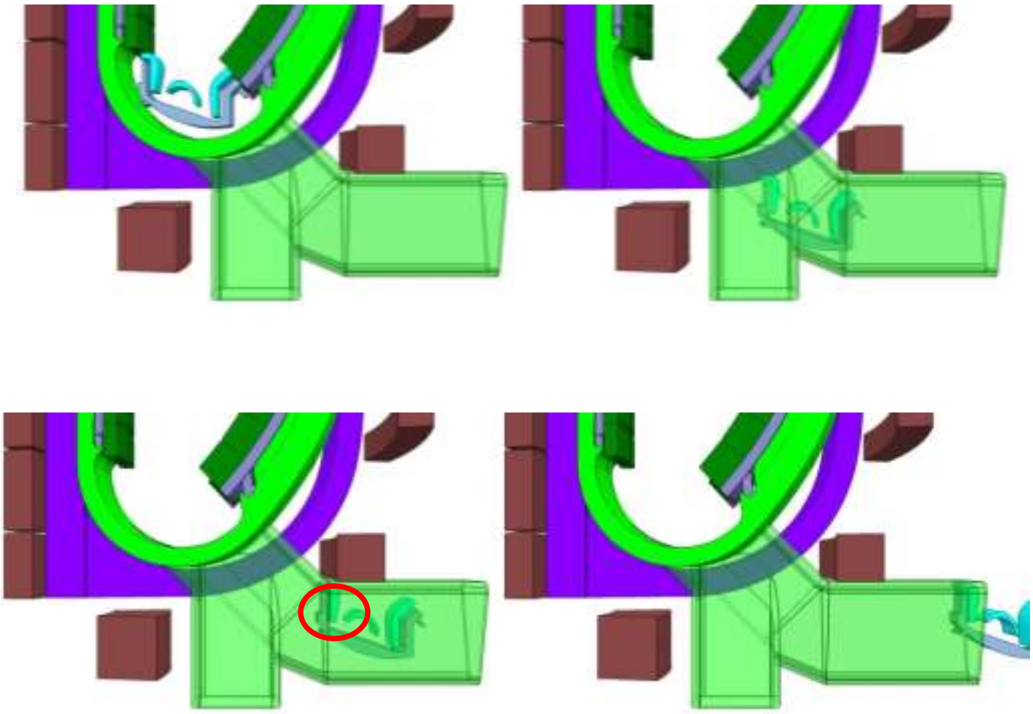

Figure 3.26 - Divertor cassette removal sequence in the hybrid port

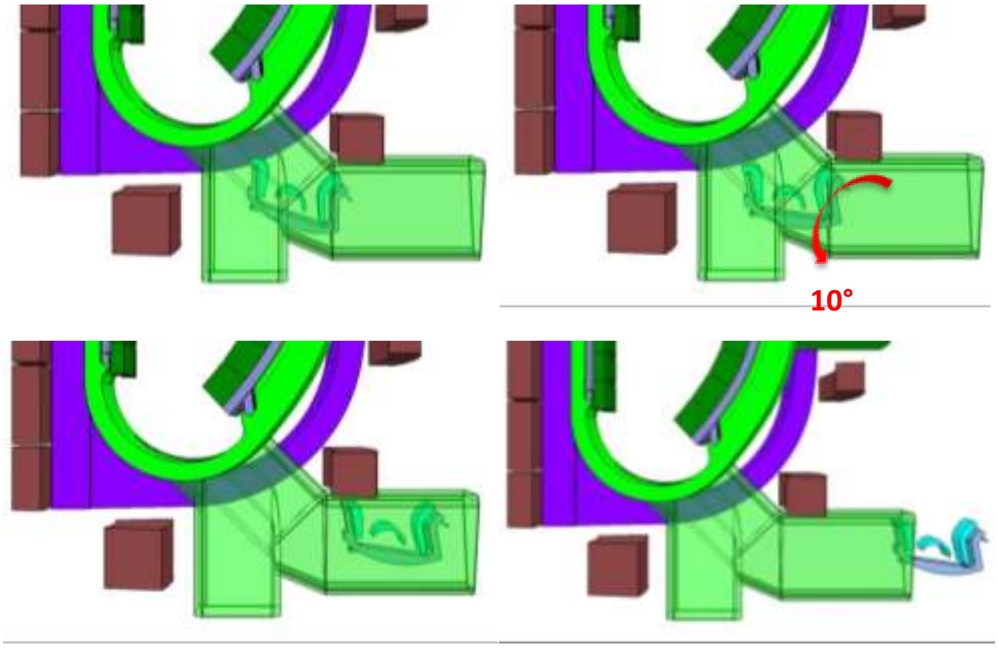

Figure 3.27 - Proposed divertor removal sequence in the hybrid port

3.4.4. *Vertical Port*

The vertical port scenario has been taking into account in these analyses. There are two possible principles to perform the DC maintenance operations. The first consist in have a vertical lower port, combining the vertical port foreseen for the vacuum pumping operation and the lower port foreseen for the DC maintenance. The second configuration is the vertical upper port. Nevertheless, this last scenario, as will be explained in the following section, has a relevant impact on the current design of the blanket and its remote handling operations.

3.4.4.1. Vertical Lower Port

The vertical lower port configuration is shown in Figure 3.28.

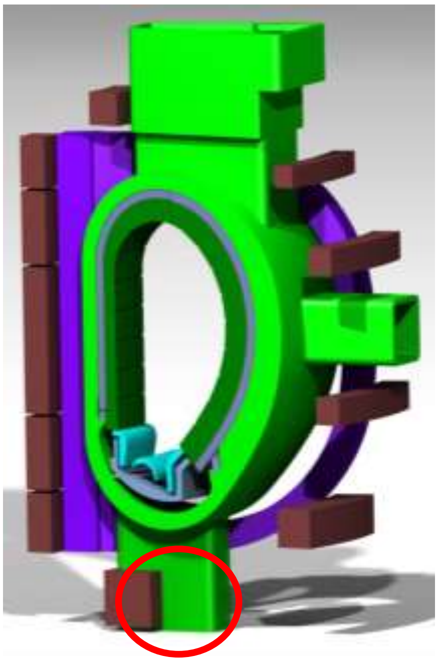

Figure 3.28 - *DEMO divertor vertical lower port*

This configuration is in conflict with the current position of the magnets due to interference problems Figure 3.29.

Figure 3.29 - Interference with the vertical lower port and the PF coils

The sequence of installation/removal of the DC can be performed by a DC mover able to lift the cassette in vertical direction. An example is shown in Figure 3.30.

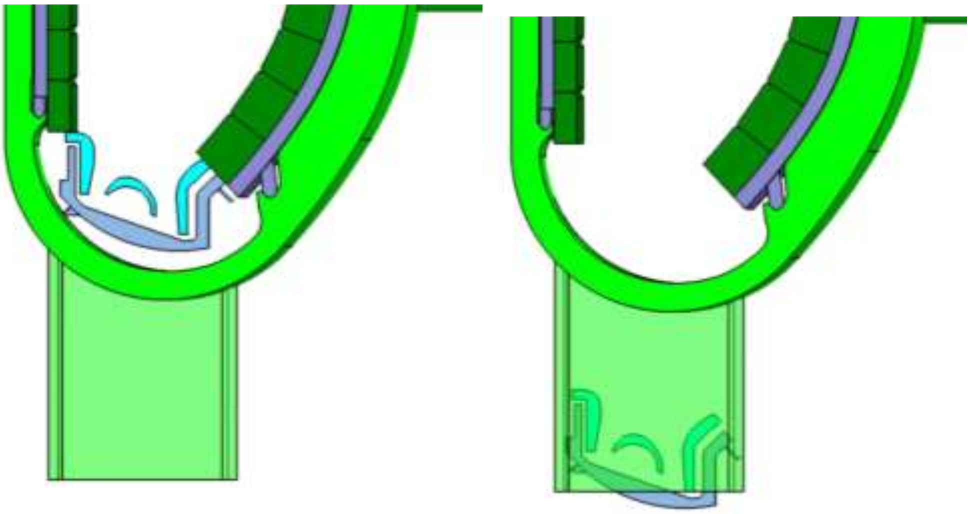

Figure 3.30 - DEMO divertor removal sequence in the vertical lower port

3.4.4.2. Vertical Upper Port

The last configuration of this preliminary study foresees the DC removal from the vertical upper port, Figure 3.31.

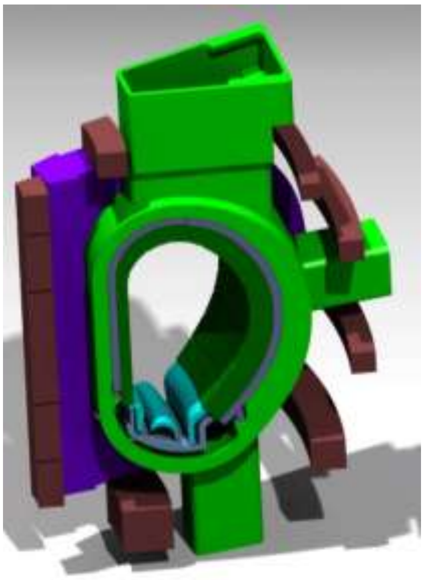

Figure 3.31 - DEMO divertor vertical upper port

Two different preliminary analyses have been made. A high level consistency analysis has been conducted between this design choice and the assumptions made in the baseline documents such as DEMO Plant Requirement Document (PRD) [18] and WPRM Project Management Plan (PMP) [19].

An additional preliminary analysis has been conducted in order to evaluate the possibility to remove the cassettes from the vertical upper port. The main goal has been to address all the critical issues related to this design choice, evaluate all impacts on the plasma facing components and their remote handling tools design.

In order to access to the DC area from the vertical upper port, the remote handling equipment (RHE) will work in-vessel, where the level of radiation is very high. In detail according to the preliminary assessment of DEMO Remote Maintenance [20], the maximum photon absorbed dose rates of typical materials used by RHE (Remote Handling Equipment) is 1.500 Gy/hr in-vessel and 80 Gy/hr in a port after one month by the last plasma pulse, because of this all the RHE shall be designed to withstand an aggressive level of radiation. This aspects are clearly inconsistent with the assumptions of the WPRM´s PMP [19] in which is cited "*Specific maintenance schemes will have to be used that eliminates complex in-vessel operation* ". It should be noted that designing RHE that could work in aggressive environment has a big impact on their investments cost. Such as cited in WPRM´s PMP [4] "*The development of the remote maintenance system for DEMO will be driven by the need of minimizing plant down-time and maximizing availability, the strongest driver to a low cost electricity".*

As above highlighted, there are some aspects not consistent with the most important drive concepts of the DEMO design approach [17].

In order to remove the divertor cassettes from the vertical upper port only two solutions are feasible with the current design of the tokamak. In the first solution, the Central Outboard Blanket Segment (COBS) shall at first be removed in order to leave enough space to uninstall the central and the others cassette. This solution avoids impacts on the design of the Blanket Segments (BS), but has huge effect on the time spent for RH operations of the plasma facing components, moreover the COBS uninstalled during the cassettes RH activities shall be stored in a dedicated area. It should be noted that these aspects could not be negligible, because contributes to the increase of the time for RH activities, in this case the design choice could be not consistent with the maximization of the availability of the tokamak [17].

Some problems of interferences shall be investigated as well, when the conceptual design of the DC will be ready. Figure 3.32 shows the interference between the bounding box of the DC with the Left Outboard Blanket Segment (LOBS) and the Right Outboard Blanket Segment (ROBS).

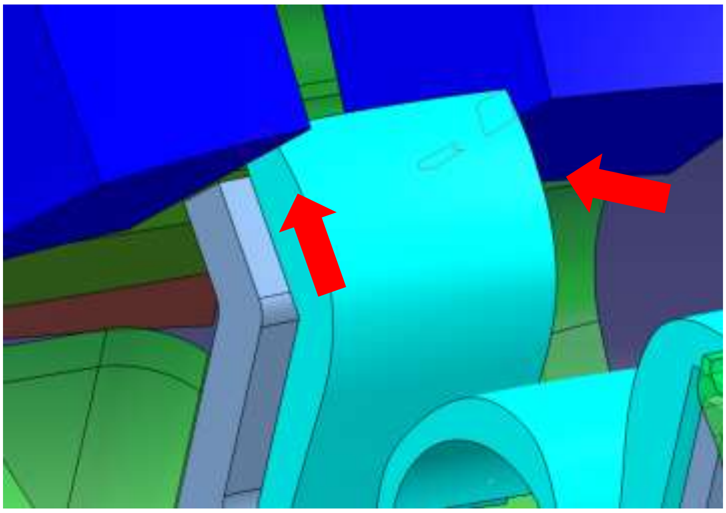

Figure 3.32 - Interferences *of the divertor cassette with LOBS and ROBS during vertical lifting*

Regarding the design of the DC RHE, the only location where could be possible grab the cassette is the dome area Figure 3.33. It should be noted that the estimated weight of a single cassette is about 17 tons. Moreover, after its lifecycle the dome area will be weakened by the high loads and radiation level [20]. Studies on the embrittlement of the cassettes materials shall be carried out to define if at the end of a cassette lifecycle the dome could be able to withstand the total weight of the DC during the RH activities.

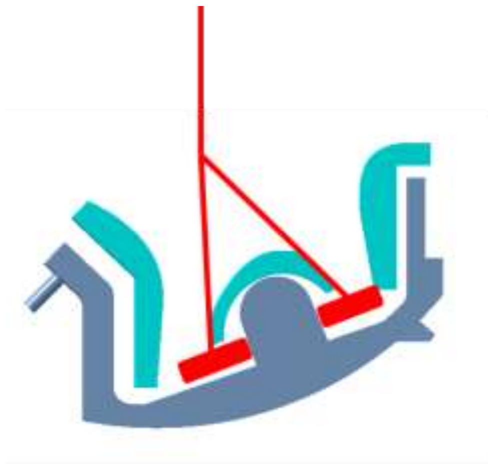

Figure 3.33 - *Vertical lifting principle of the divertor cassette*

The kinematic sequence of the first approach is shown in Figure 3.34 .

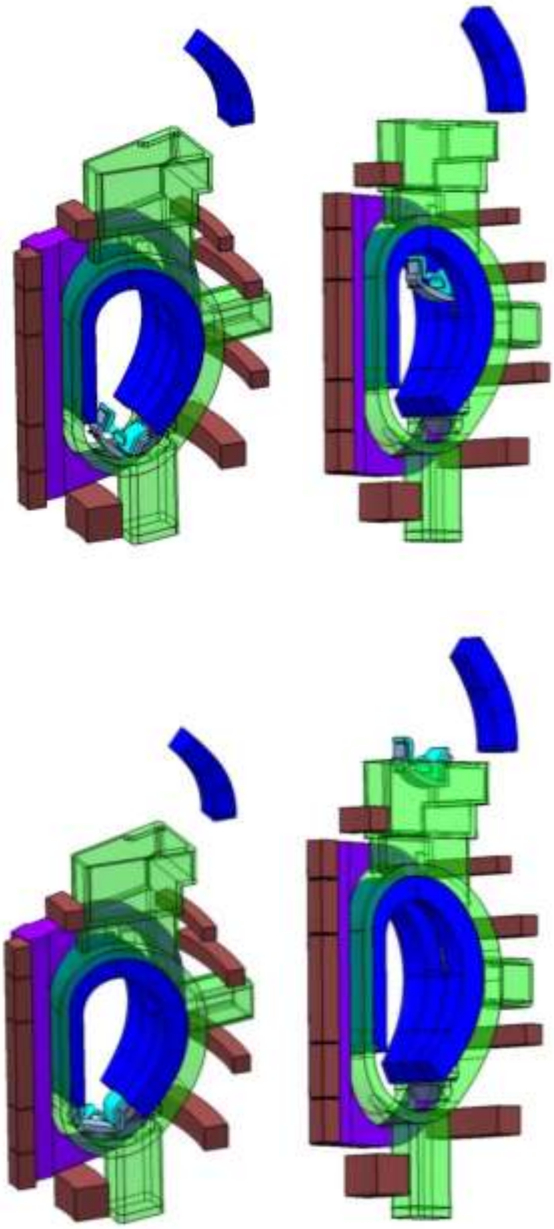

Figure 3.34 - First proposed divertor removal sequence in the vertical upper port

The second solution takes into account changes at the current design of the BSs and their RHE [21]. In particular the COBS shall be divided in two different segments: upper and lower segments Figure 3.35. These changes will have a heavy impact on the design of the BS but also on theirs RHE. Furthermore estimated time for the RH operations can be also increased.

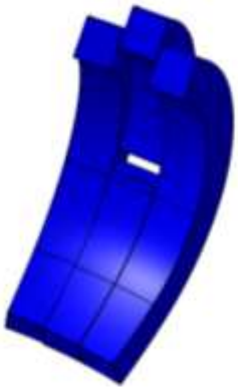

Figure 3.35 - *Proposed COBS modification*

The simulation of the second configuration is shown in Figure 3.36.

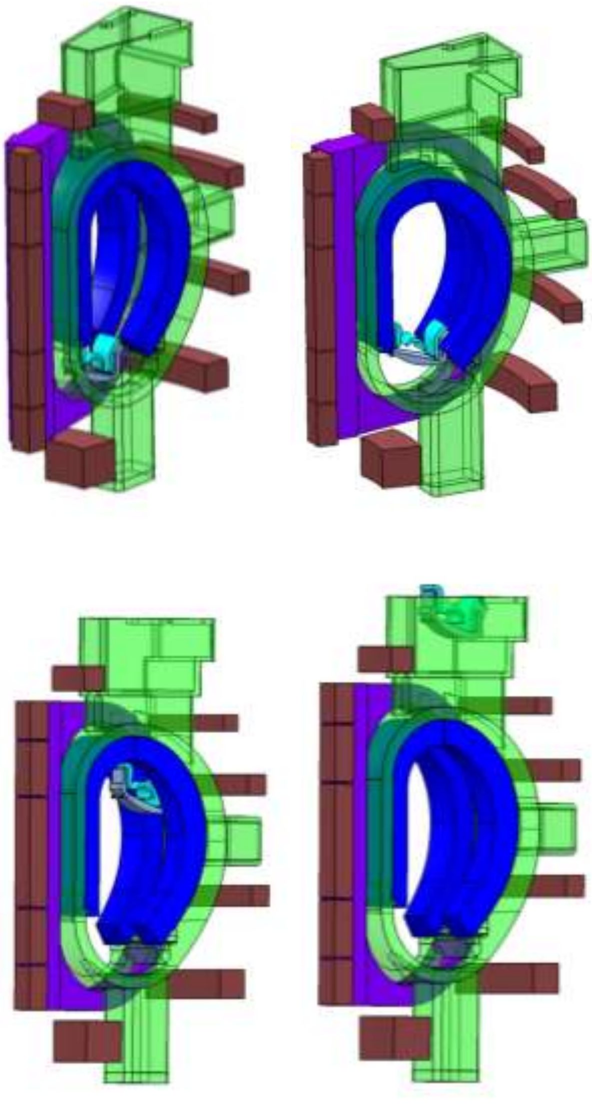

Figure 3.36 - *Second proposed divertor removal sequence in the vertical upper port*

It is clear that these solutions are inconsistent with the current RH assumptions. In particular with assumption that divertor shall be carried out with the presence of the Blanket Modules. Also in this case the time to spend in the RH activities is increased with a decreasing of the DEMO availability, this aspect is clearly non-consistent with the needs cited in DEMO´s WPRM PMP.

As aforementioned in the previous paragraphs the remote maintenance design team conducted a preliminary assessment on different configuration of DEMO VV geometry, the results of the assessment and the sketch of different geometry of the lower port have been exchanged with DEMO VV design team. It should be noted that this activity is still in progress.

3.5 Structural Assessment on DEMO VV conceptual design

The vacuum vessel (VV) is a key component of the Demonstration Fusion Power Reactor (DEMO), the primary functions of the VV are to provide the first confinement barrier, withstand postulated accidents without loosing confinement, remove the nuclear heating, and provide a boundary consistent with the generation and maintenance of a high quality vacuum and support in-vessel components and their loads. Starting from the results and outcomes of the activities described in the previous paragraphs a preliminary assessment on the DEMO VV conceptual design has been made. The main driver of the work consisted in a preliminary assessment on the DEMO VV structures in order to identify, already in this embryonal phase, any criticalities in the current design of DEMO VV.

3.5.1. *Elastoplastic analyses on a single sector Of DEMO Vacuum Vessel*

All the analyses performed have been run according to RB3242 by RCC MRx [14]. In order to perform the analyses five VV supports layouts have been provided. For each configuration four supports have been modelled. Each support is joined to one port sidewall (Figure 3.37).

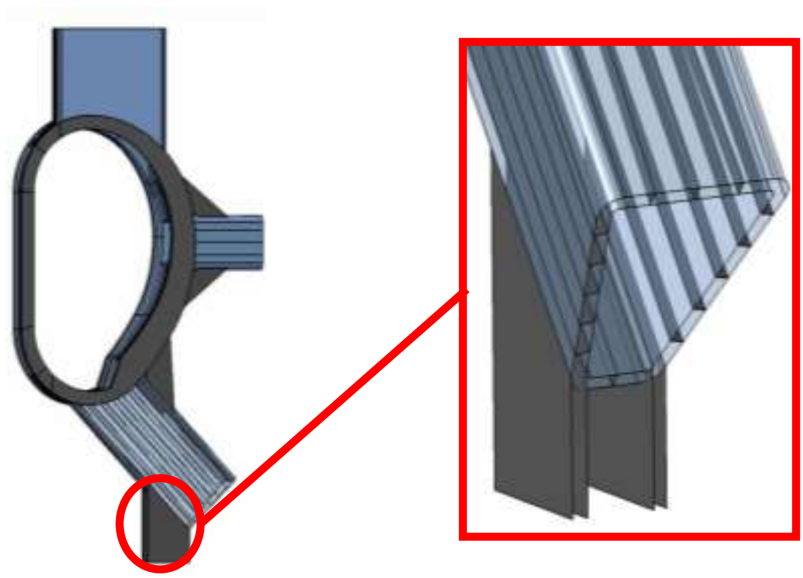

Figure 3.37 Supports on the lower port joined to the four port sidewall

The configurations provided are:

- ✓ **L5 configuration**: the supports are placed on the lower port and the distance between the supports and tokamak axis is about 13700mm, their length is 2120 mm (Figure 3.38).

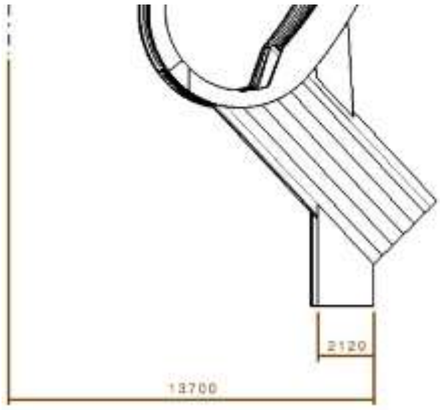

Figure 3.38 L5 Supports configuration

- ✓ **L2 configuration**: the supports are placed on the lower port and the distance between the supports and tokamak axis is about 12640mm, theirs length is 2120mm (Figure 3.39).

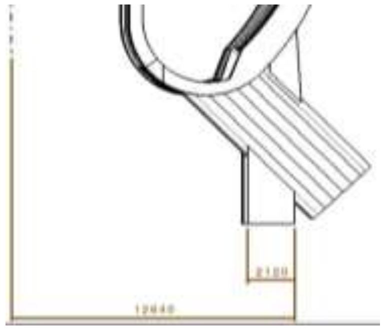

Figure 3.39 L2 supports configuration

- ✓ **L1 configuration**: the supports are placed on the lower port and the distance between the supports and tokamak axis is about 11580mm, their length is 2120mm (Figure 3.40).

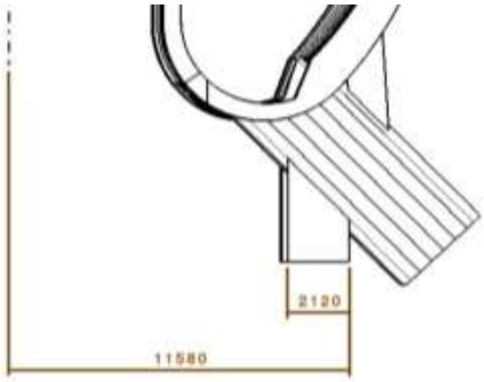

Figure 3.40 L1 supports configuration

- **E1 and E2 configurations**: the distance between the supports and tokamak axis is about 17340mm, their length is 1500mm (Figure 3.41), the supports are placed on the central port.

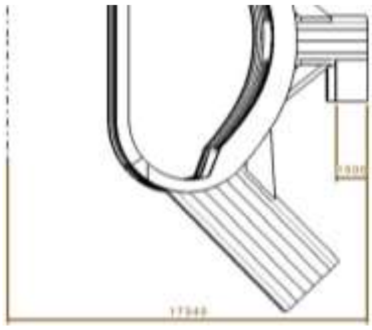

Figure 3.41 E1-E2 Supports configuration

In order to better assess behaviour of the main structure and others component (gussets and ports) of the vessel, 12 load cases have been run. Each load case (LC) has been obtained combining different layout of the supports, different boundary conditions and different material gussets behaviours. LCs provided and their characteristics are listed in Table 3.2.

Table 3.2 Load cases characteristics

Load Case	Constraint Radial Coordinate [mm]	Support Location	Displacement along axis of the cylindrical coordinates system			Material Gussets behaviour
			Ux Radial direction	Uy Toroidal direction	Uz	
1	13700	L5	0	0	0	Elasto-plastic
2	13700	L5	0	0	0	Linear elastic
3	13700	L5	free	0	0	Elasto-plastic
4	13700	L5	free	0	0	Linear elastic
5	12640	L2	0	0	0	Elasto-plastic
6	11580	L1	0	0	0	Elasto-plastic
7	12640	L2	free	0	0	Elasto-plastic
8	11580	L1	free	0	0	Elasto-plastic
9	17340	E1	free	0	0	Linear elastic
10	15845	E2	free	0	0	Linear elastic
11	17340	E1	free	0	0	Elasto-plastic
12	15845	E2	free	0	0	Elasto-plastic

3.5.2. *Units and coordinate system*

The units used in the model are [mm,N]. The coordinate system considered is a **Cylindrical** coordinate system on which the origin is aligned to the origin of the tokamak coordinate system provided by CAD model **Errore. L'origine riferimento non è stata trovata.Errore. L'origine riferimento non è stata trovata.**. Directions of the coordinate system are:

- x radial direction
- y toroidal direction
- z vertical direction

3.5.3. *Material Types*

The material considered is AISI 316 L(N). Three different material types have been defined in FE model (Table 3.3). Material property values are defined for the operating temperature (100° C).

Table 3.3 Material Types properties

Description	E [Pa]	ν	Density [kg/m^{-3}]	Behaviour
Stainless steel custom	**1,93·10^{11}**	**0.3**	**24851**	**Elasto - plastic**
Stainless Steel	**1,93·10^{11}**	**0.3**	**7850**	**Linear Elastic**
Stainless Steel high stiffness	**1·10^{16}**	**0.3**	**7850**	**Linear Elastic**

- **Material type: Stainless steel custom** was applied to the main structure of the VV and ports. It should be noted that in this case density value has been calculated taking into account not only weight of the main vessel, but also weights of the others components (port extensions, duct, plugs, in-wall shielding, blanket modules, divertor cassettes) [3]. The material behaviour is elastoplastic. In Table 3.4 is shown the relationship of the minimum true stress-strain curve for stainless steel 316L(N), this characteristic has been applied to stainless steel custom material type to simulate an elasto-plastic behaviour.

Table 3.4 Stress-strain relationship of the minimum true stress-strain curve for stell 316 L(N),[4]

Operating temperature = 100°C	
Plastic Strain [mm^{-1}]	**Stress [Pa]**
2.69·10^{-4}	50·10^{+6}
5.54·10^{-4}	100·10^{+6}
7.88·10^{-4}	125·10^{+6}
10.69·10^{-4}	140·10^{+6}
13.92·10^{-4}	150·10^{+6}
18.99·10^{-4}	160·10^{+6}

$26.94 \cdot 10^{-4}$	$170 \cdot 10^{+6}$
$39.26 \cdot 10^{-4}$	$181 \cdot 10^{+6}$
$58.01 \cdot 10^{-4}$	$191 \cdot 10^{+6}$
$86.05 \cdot 10^{-4}$	$202 \cdot 10^{+6}$
$127.23 \cdot 10^{-4}$	$213 \cdot 10^{+6}$
$3910.28 \cdot 10^{-4}$	677·10+6

- **Material Type: Stainless Steel** was applied, in the some load cases, to the gussets to investigate the load factor of the main vessel structure. This aspect will be better illustrated in the next paragraphs.
- **Material Type: Stainless Steel high stiffness** was applied, in all load cases, to the supports of the VV. It should be noted that, current assessment did not investigate supports structures. For this reason the supports was modelled infinitely stiff to avoid their failure and to reduce singularity effects due to the constraint positions.

3.5.4. *Element Type*

The element type of the FE model is **SHELL 181**.

The FE model has (Figure 3.42):

- ✓ **91982** nodes
- ✓ **96015** elements

Figure 3.42 Mesh of DEMO VV single sector

3.5.5. *Boundary Conditions*

In all load cases a symmetry boundary condition has been placed on the left edge (-11,25° in cylindrical coordinate system) and on the right edge (11,25° in cylindrical coordinate system) of the VV sector (red line Figure 3.43).

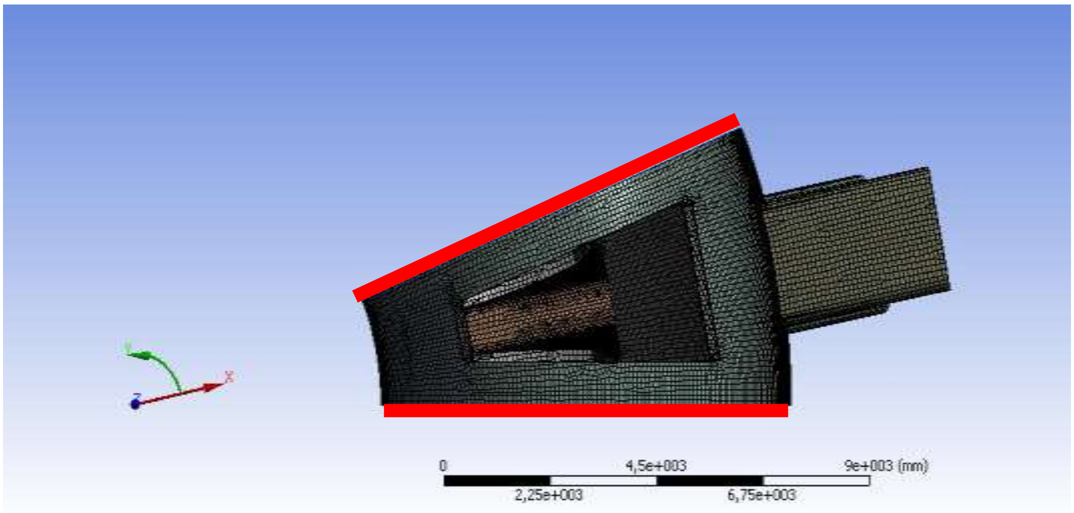

Figure 3.43 Symmetry boundary conditions on the left and right edges of VV single sector

It should be noted that, in order to allow rotations in x-z planes, constraints have been placed just on one node for each support. In Figure 3.44 the yellow flag note shows exact constraint position.

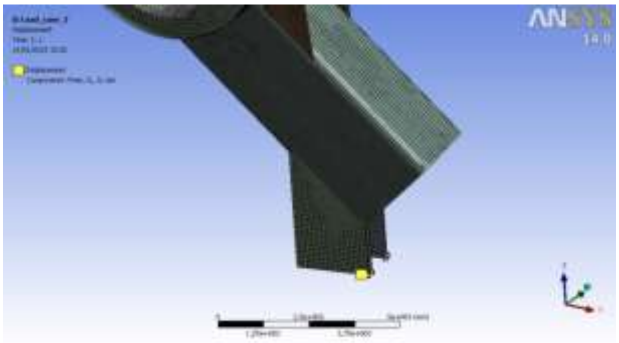

Figure 3.44 Boundary Condition on the FE Model

3.5.6. *Loads application and weights*

In the FEM analyses performed, the load was increased in multiple load steps until the structure collapses, each step increases the load values by 20%. The structure cannot bear any load greater than the limit collapse load due to high plastic deformation. The load is applied to the deformed structure.

Table 3.5 Load combinations occurs in VDEIII [3]

Case	Fvert [N]	Fsideways [N]
VDEIII slow down 1	$1{,}46 \cdot 10^{8}$	$1{,}35 \cdot 10^{7}$
VDEIII slow down 2	$7{,}30 \cdot 10^{7}$	$2{,}70 \cdot 10^{7}$
VDEIII slow up 1	$-7{,}30 \cdot 10^{7}$	$5{,}40 \cdot 10^{7}$

The net vertical load applied on each sector was:

$$\frac{F_{VEDIII\_slow\_down\_1}}{n\_sectors} = \frac{1,46 \cdot 10^8}{16} = 9,12 \cdot 10^6 \, [\mathrm{N}]$$

Gravity acceleration has been applied to the FE model to take into account weights of all VV structures. The total mass of DEMO single sector, considering also the other structures (port extensions, duct, plugs, in-wall shielding, blanket modules, divertor cassettes) [3] is:

$$\mathrm{W_{single\ sector}} = 1,15 \cdot 10^6 \, [\mathrm{kg}]$$

The DEMO tokamak mass is:

$$W_{tokamak} = W_{single\ sector} * 16 = 1,85 \cdot 10^7\ [kg]$$

The load was applied on the red surface in Figure 3.45, its direction is shown by red arrow. In particular, the force direction is parallel to the z axis and its verse is negative with respect to the cylindrical coordinate system.

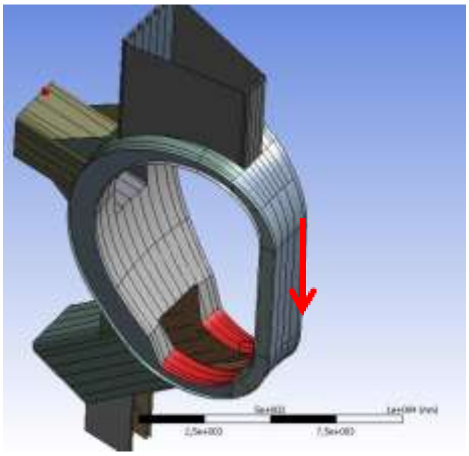

Figure 3.45 Direction and verse of the load

It should be noted that the total mass of the model was checked to be correct through reaction force calculation. The load combination considered in the task was:

Category 3: Class C: Dead weight + VDEIII [4]

3.5.7. *Results*

As aforementioned, in the elastoplastic analyses, load is increased in multiple load steps until the structure collapses. In this way the structure cannot bear any load greater than the limit collapse load due to high plastic deformation. Moreover the load is applied to the deformed structure. In the following Table 3.6 are reported the load cases results.

Table 3.6 Results Summary

Load Case	Ultimate Load Factor	Time of Last Solution	Comments
1	7,99	39,97	Instability phenomenon on the gussets; high plastic strain on the joint area between lower port and main vessel; VV thermal expansion is not allowed.

2	9,05	45,23	High plastic strain on the joint between lower port and main vessel; the LC estimates how much force main vessel can withstand (gussets not included); VV thermal expansion is not allowed.
3	2,53	12,63	Lower port gussets collapse and are affected by instability phenomenon
4	7,98	39,92	High plastic strain; the LC estimate how much force main vessel con withstand (gussets not included); VV thermal expansion is allowed.
5	8,76	43,79	Instability phenomenon on the gussets; plastic strain and last LF are higher than LC 1; high plastic strain on the joint area between lower port and main vessel; VV thermal expansion is not allowed.
6	8,89	44,45	Collapse is on joint area between lower port and main vessel, plastic strain and last LF are higher than LC1 and LC5, gussets are not affected by instability phenomenon; VV thermal expansion is not allowed.
7	3,29	16,46	Lower port gussets collapse and are affected by instability phenomenon
8	4,62	23,11	Lower port gussets collapse and are affected by instability phenomenon
9	2,66	13,29	Central port sidewalls collapses; the LC estimates how much force main vessel can withstand (gussets not included); VV thermal expansion is allowed.
10	4,55	22,76	Instability phenomenon occurs on the sidewalls of the central port, VV thermal expansion is allowed
11	2,88	14,4	Collapse occurs both on the upper gussets of the central port and on the port sidewalls
12	4,24	21,2	Collapse occurs both on the gussets of the central port and on its sidewalls. Maximum plastic strain is too high. All that caused by stress concentration due to joint between materials type with different behaviours

In the Table 3.6 are reported for each load case the ultimate load factor that represents how much load DEMO VV can withstand. The realistic load case are LC3,LC7, LC8, LC9, LC11, LC12. In all realistic LCs the gussets collapse. The gussets in this configuration represent the most critical components.

3.5.7.1. Reaction Forces

In Table 3.7 are listed the reaction forces in cylindrical coordinate system.

Table 3.7 Reaction forces for each load case along cylindrical coordinate system

Load Case	Ultimate Load Factor	Time of Last Solution	Reaction Force Rx (Radial) [N]	Reaction Force Ry (Toroidal) [N]	Reaction Force Rz (Vertical) [MN]
1	7,995	39,975	-7,17E+07	1,76E+03	161
2	9,0458	45,229	-7,26E+07	5,55E+05	180
3	2,5266	12,633	0,00E+00	-5,85E+06	49.1
4	7,983	39,915	0,00E+00	-2,16E+06	125
5	8,7582	43,791	-6,32E+07	3,61E+04	177
6	8,8904	44,452	-4,62E+07	-3,64E+05	179
7	3,2924	16,462	0,00E+00	-5,63E+06	64.4
8	4,6212	23,106	0,00E+00	-5,51E+06	90.4
9	2,658	13,29	0,00E+00	-2,46E+06	48.3
10	4,5528	22,764	0,00E+00	-1,39E+06	80.4
11	2,88	14,4	0,00E+00	-1,83E+06	47.3
12	4,24	21,2	0,00E+00	-1,07E+06	77.2

In Figure 3.46 LFs of the LCs with elastoplastic gussets behaviour and supports on the lower port have been plotted. In detail red line represents LCs on which radial coordinate is locked, blue line shows LCs with unconstrained radial displacements. On both cases when constraint radial coordinate decreases, LF increases due to a moment decrease. Moreover the graph (Figure 3.46) helps us to estimate how much force VV can withstand in case of radial displacement free and locked. As we can see if radial coordinate supports is unconstrained LF is widely reduced, this choice allows main VV thermal expansion. In other words presence of radial constraint allows a great amount of force can flow through port structures unloading gussets. As aforementioned, the most critical components are gussets and joint area between lower port and main vessel.

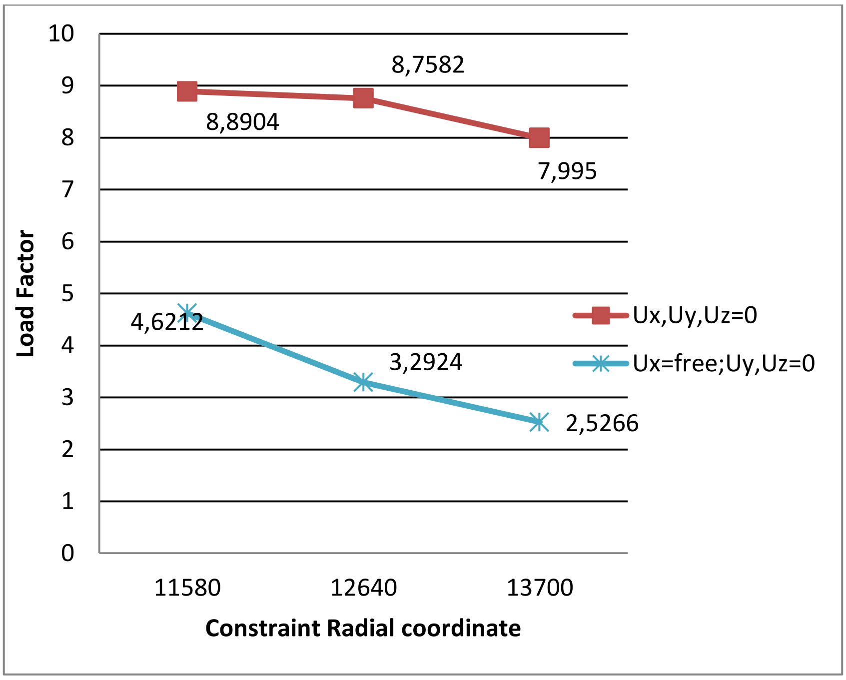

Figure 3.46 Load factors VV supports on the lower port (L1,L2, L5), gussets with elastoplastic behaviour

Figure 3.47 shows LFs of LCs on which supports are placed on the central port and the gussets have elastoplastic behaviour. In these cases sidewalls of the port are critical component, on that occurs instability phenomenon. The LF is increased when the radial coordinate of constraints is reduced.

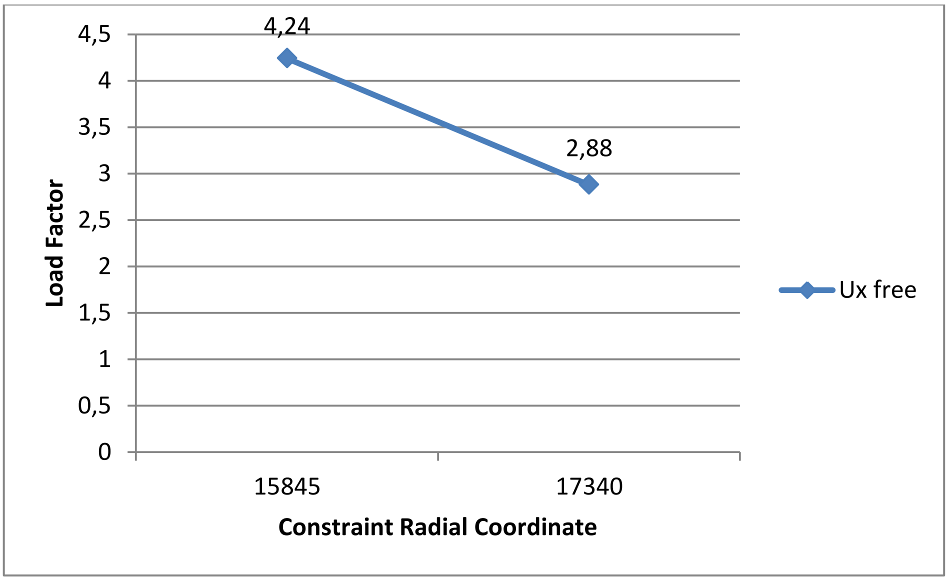

Figure 3.47 Load factors VV supports on the central port (E1, E2), gussets with elastoplastic behaviour

The DEMO VV has been assessed applying dead weight + VDEIII slow-down 1 vertical loads (worst case) to a single VV sector (Table 3.5). Moreover for each Load Case last VV load factors have been calculated. The results of elastoplastic analyses show that a radial constraint would be extremely beneficial from structural point of view (see LCs 1,5,6), unfortunately this kind of constraint cannot be implemented since vessel thermal expansion shall not be constrained. In Table 3.8 load cases similar in terms of components behaviour (both Main Vessel and Gussets with elastoplastic behaviour) and boundary condition are listed. As we can observe, in all LCs the LFs exceed the limits according to RCC-MRx – 2012 (Table 3.8). The design Criteria used in analyses is Level C criteria. The criteria check that the structure is not subjected to type P damages under loadings obtained by multiplying the loading concerned by the LF given by **Errore. L'origine riferimento non è stata trovata.**.

Table 3.8 Results of realistic load cases

Load Case	Constraint Radial Coord. [m]	Support Location	Ux	Uy	Uz	Gussets behavior	Ultimate Load Factor	Required load factor (Plastic instability according to RB 3251.12 Errore. L'origine riferimento non è stata trovata. - Errore. L'origine riferimento non è stata trovata.)
3	13.7	L5	free	0	0	elastoplastic	2,53	2,0
7	12.6	L2	free	0	0	elastoplastic	3,29	
8	11.6	L1	free	0	0	elastoplastic	4,62	
11	17.3	E1	free	0	0	elastoplastic	2,88	
12	15.8	E2	free	0	0	elastoplastic	4,24	

As aforementioned, according to RCC-MR rules the strength of the main vessel is sufficient to withstand the most severe vertical loads (VDE and dead weight). The vessel could be supported at the equatorial ports or at the lower ports; both port structures are capable to provide sufficient strength in case gussets are implemented in the design as reinforcements. It was noted that the inclination of the lower port is very beneficial for the vessel's load bearing capability. Since regarding the integration with the magnet supports the lower port seems a more suitable candidate to support the vessel, the design and inclination of the lower port should be a focus of future work.

3.6 Conclusion

The work developed by three different design teams has been illustrated in this chapter. The teams were located physically in different places and each team development a different aspect of the same product. Our study was focused on the management of the exchange data. These activities highlighted the criticalities in the exchange of data between design team with different background. In order to optimize the design process the most important need consists in the presence of common rulers of data exchange between teams. In case of complex product a key design team that manage the rules and the exchange data, contributes to optimize the design process. In detail the main objective of the key team will consist in "*Don't give all information to everyone but the right information to the right people*". Finally it should be noted that all design activities are still in progress, the research on the management of the exchange data and application of VR engineering tools supporting the design will continue.

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Chapter 4 *Industrial application: Preliminary piping layout and integration of European Test Blanket Modules subsystems in International Thermonuclear Experimental Reactor (ITER)*

4.1 Introduction

This activity explores a possible integration of some ancillary systems of helium-cooled lithium lead (HCLL) and helium-cooled pebble-bed (HCPB) test blanket modules in ITER CVCS area. Computer-aided design and ergonomics simulation tools have been fundamental not only to define suitable routes for pipes, but also to quickly check for maintainability of equipment and in-line components. In particular, accessibility of equipment and systems has been investigated from the very first stages of the design using digital human models. In some cases, the digital simulations have resulted in changes in the initial space reservations.

4.2 Overview

Nuclear reactions inside the plasma chamber heat up the blanket materials because of both nuclear fusion and neutrons slowing-down. Thus, the generated thermal power must be extracted by a suitable coolant. Within the European fusion program, several test blanket modules (TBMs) are to be tested in the International Thermonuclear Experimental Reactor (ITER). In particular, our work focuses on piping layout and integration of the two Helium Cooling Systems (HCSs) that serve Helium-Cooled Lithium Lead (HCLL) and Helium-Cooled Pebble-Bed (HCPB) Test Blanket Modules [1], [2] inside the Tokamak building.

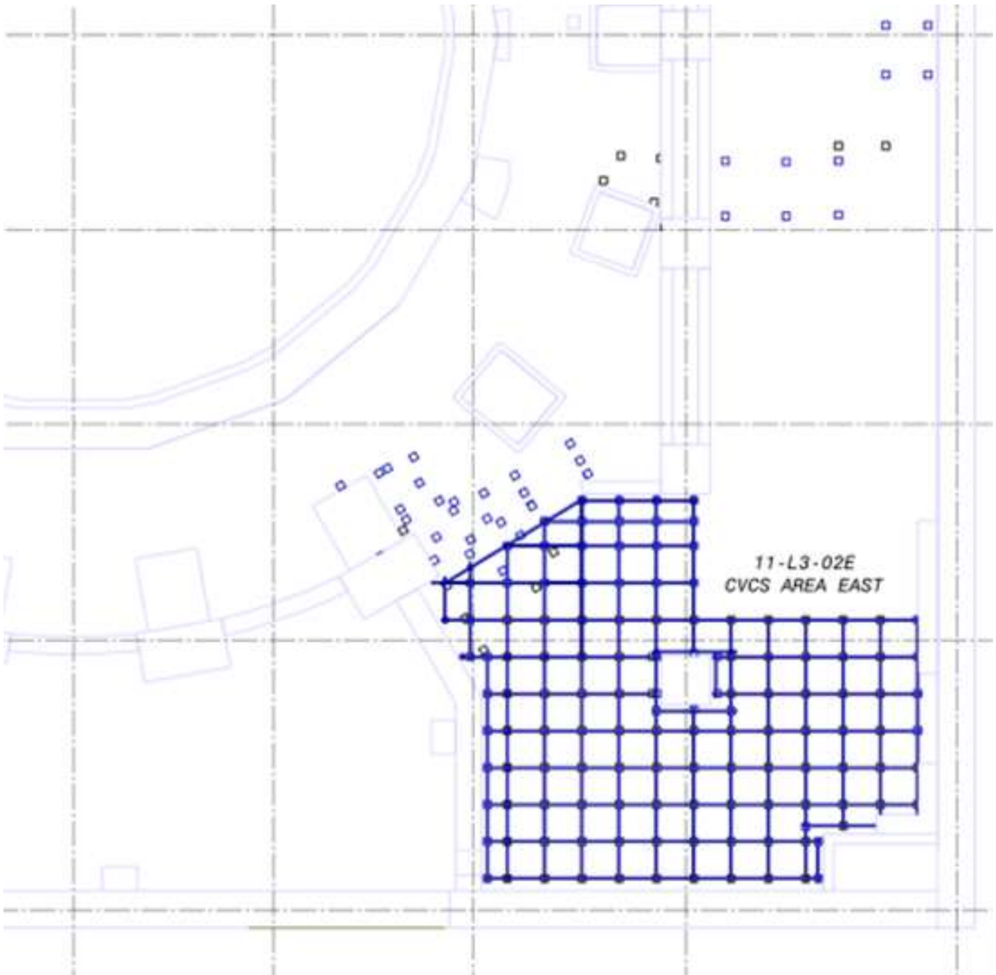

Figure 4.1 Location of "CVCS Area" East with respect to the Tokamak building

The primary function of the HCS is to extract the thermal power deposited in the Test Blanket Module (TBM) due to the plasma radiation and neutron interaction and transfer it to the ITER Heat Rejection System (HRS) via the intermediate Component Cooling Water System (CCWS). Moreover, HCS will extract the decay heat during the reactor shutdown. The main components of the HCS loop will be hosted in the Chemical and Volume Control System (CVCS) Area East (11-L3-02E), which is located inside the Tokamak building (see Figure 4.1).

However, in addition to HCS, "CVCS Area" will also host the Coolant Purification System (CPS) [3]. The overall space available at floor level for HCS and CPS subsystems in "CVCS Area" is about 220m^2 (see Figure 4.2).

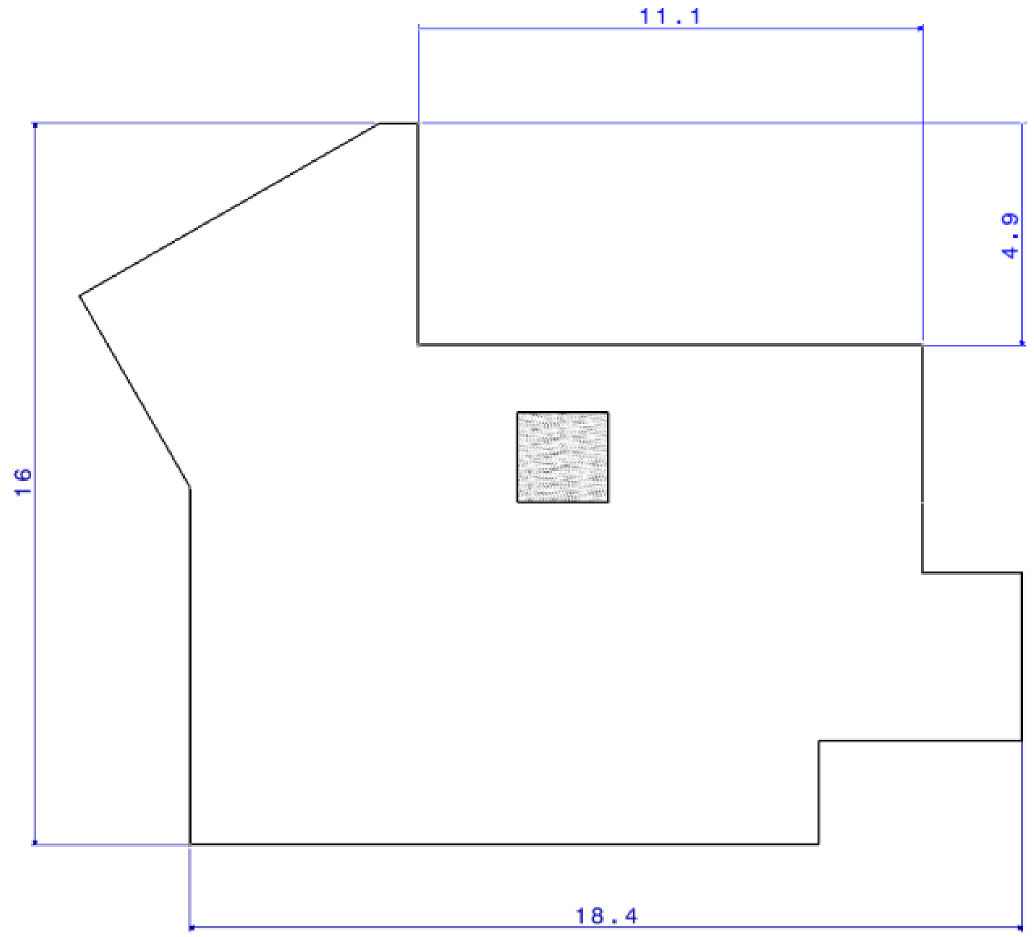

Figure 4.2 Overall dimensions (m) of space reserved for HCS and CPS in ITER "CVCS Area"

More precisely, the design activities to be described in the present paper concerned:

- ✓ Integration of HCS and CPS subsystems in "CVCS Area", taking into account the safety requirements and the space constraints, as well as the maintenance/access scheme,
- ✓ Preliminary design of the steel frames supporting all the equipment in "CVCS Area".

Integration activity is fundamental not only to properly arrange equipment and piping lines, but also to provide service walkways and preliminarily check for maintainability of systems and safety of workers.

In any case, the piping system aimed at transporting the fluids among the different equipment must be properly designed. This task is quite complicated because many different aspects have to be considered. In particular:

- ✓ Piping design and equipment arrangement are interrelated subjects,

- ✓ Many environmental constraints have to be taken into account (e.g. electrical systems, water interfaces, heating, ventilation and air conditioning systems, etc.),
- ✓ Several codes and standards must be met, depending on the specific application,
- ✓ Maintenance and safety issues have to be carefully considered,
- ✓ Different possible sources of stress have to be identified and properly addressed (e.g. thermal stress, weights, seismic loads, etc.),
- ✓ Apparently similar routing solutions can have considerably different impact on the final costs,
- ✓ Adequate space must be reserved for ancillary systems and instrumentations (whether or not completely designed) and maintenance walkways,
- ✓ Frames that shall support pipes, valves and instrumentations, as well as anchor systems have to be also considered.

Today piping design is mostly conducted by means of specific CAD tools that help designers to properly address almost all the constraints aforementioned. With reference to ITER project, CATIA V5 by *Dassault Systémes* is the CAD tool selected for 2D/3D design. The piping design workflow with CATIA is quite well-established [4]. Indeed, CATIA provides many modules for plant design that help designers to place equipment, route pipes, make space reservations, build support structures, provide walkways, etc.

However, as mentioned, most of the components of a piping system must be placed in view of maintenance. CATIA V5 includes another module, namely *"Human Builde*r", that allow 3D designers to perform ergonomic evaluations inside the same CAD environment by means of digital representations of humans, known as Digital Human Models (DHM) [5] [6]. *Human Builder* can be used to quickly check systems for maintainability as well as to preliminarily study worker ergonomics [7].

Although, at the current stage of HCS design, a complete Reliability, Availability, Maintainability and Inspectability (RAMI) analysis [8] is not available yet, *Human Builder* module has been used to quickly check for accessibility of the main components inside "CVCS Area" and, in some cases, to evaluate maintenance postures (see Figure 4.3).

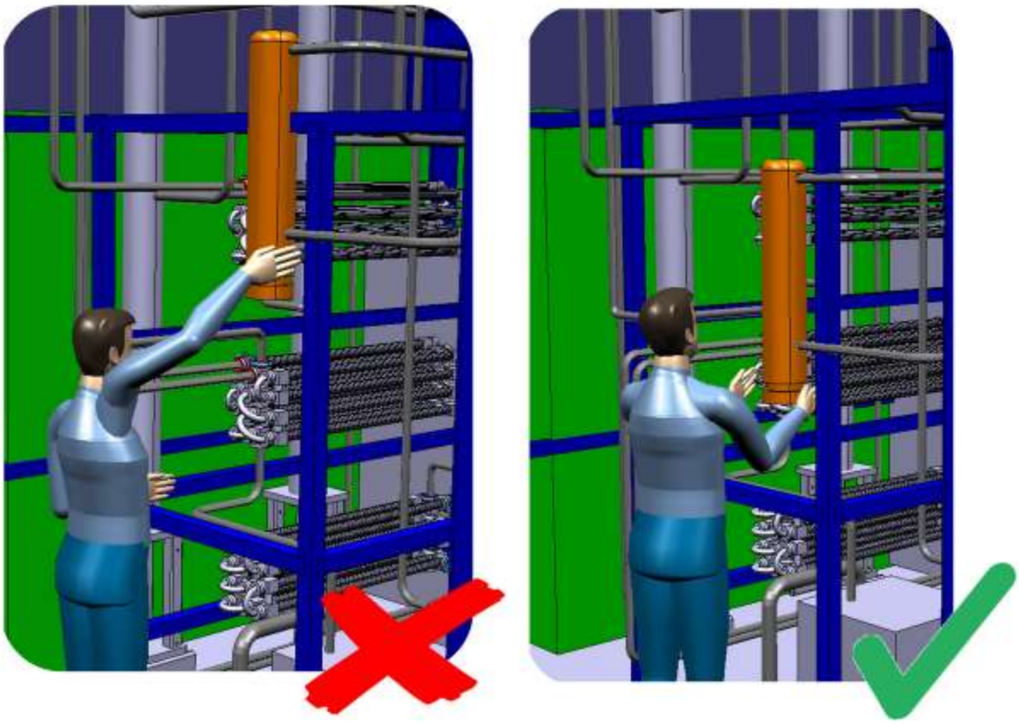

Figure 4.3 Digital humans have been used to place components in view of their accessibility and maintenance

The integration activity in "CVCS Area" started from the pre-conceptual design of HCS discussed in [1], in order to:

- ✓ Update the piping lines of HCLL and HCPB HCSs according to the latest Process Flow Diagrams (PFDs),
- ✓ Integrate the 4" valves, new filters and new economizers in HCLL and HCPB HCS circuits,
- ✓ Build up the HCLL and the HCPB CPS subsystems according to the latest PFDs,
- ✓ Preliminary design of the steel frames supporting all the equipment and valves

Piping layout design for HCS and CPS will be described in more detail in the following sub-sections.

4.3 Piping layout design of HCS

The PFDs of the two HCS process loops have been substantially changed since the pre-conceptual design [1]. As shown in Figure 4.4, the initial design was lacking of any control valve, while the DN100 piping took up almost the entire "CVCS Area". Just two reservation volumes (1800x2250x3000 mm) were left for CPS sub-systems (not yet defined at the time of that pre-conceptual design).

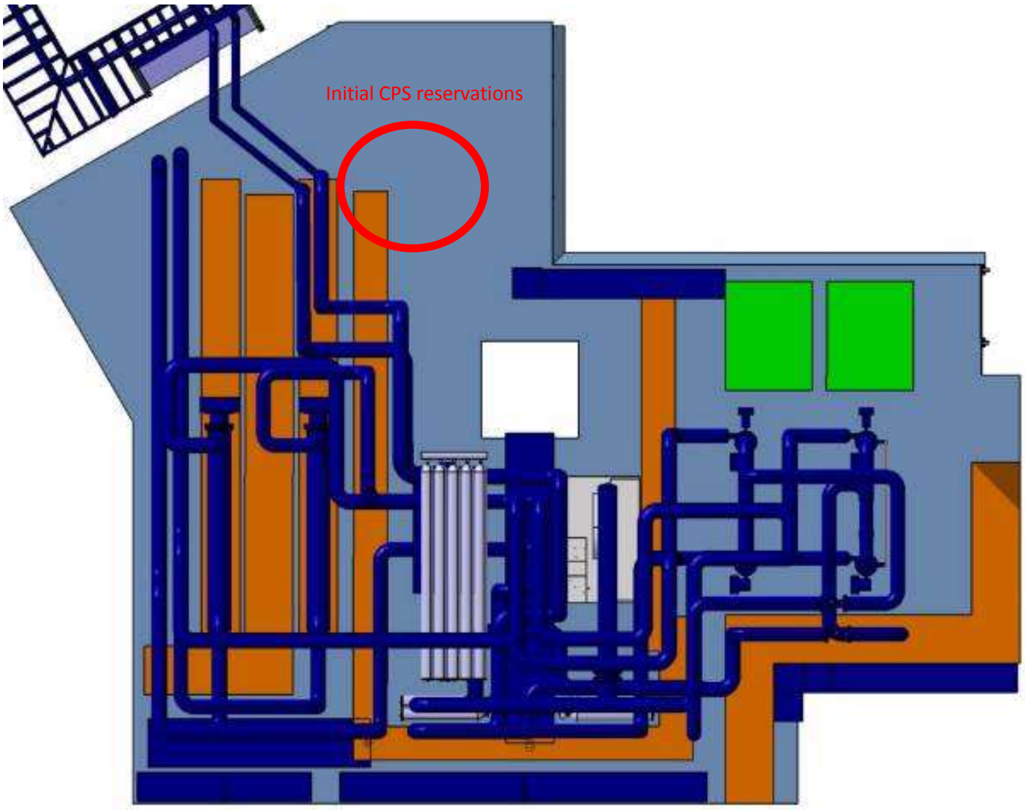

Figure 4.4 Pre-conceptual design of HCS in "CVCS Area"

In particular, new filters have been selected and their number has been doubled (each Turbo Compressor now has its own filter), while several valves have been added. Moreover, two classical tube-and-shell economizers have been replaced with more compact Printed-Circuit Heat Exchangers (PCHE) [9]. A Pressure Control System (PCS) has been also finalized as parts of HCS.

Our preliminary analyses showed that the space initially reserved for PCS and CPS was not enough (see Figure 4.4).

For this reason, a completely new layout for "CVCS Area" has been provided. As shown in Figure 4.5, in order to gain space for CPS and PCS equipment and pipes, "CVCS Area" has been virtually divided in three sub-areas: the one reserved for the two HCSs "main loops", which mostly use DN100 pipes, and the other for CPSs and PCSs, with DN25 and DN40 piping respectively.

This choice allowed a proper arrangement for pipes and equipment in "CVCS Area" and more space for maintenance.

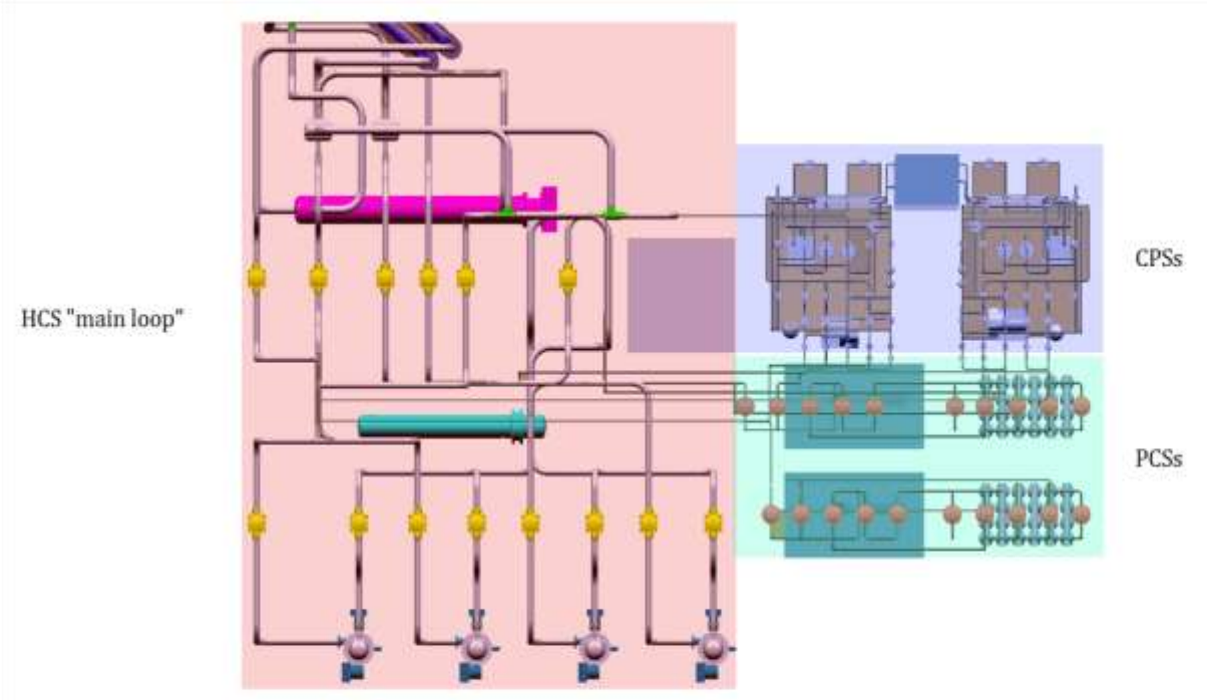

Figure 4.5 New zoning for CVCS Area

With reference to the HCS "main loop", the four turbo compressors belonging to the two HCS loops (two per loop) have been arranged in a straight line, in order that maintenance personnel could reach both the equipment and the control cubicles through a single maintenance walkway. More generally, each control cubicle has been moved as close as possible to their reference equipment (see Figure 4.6).

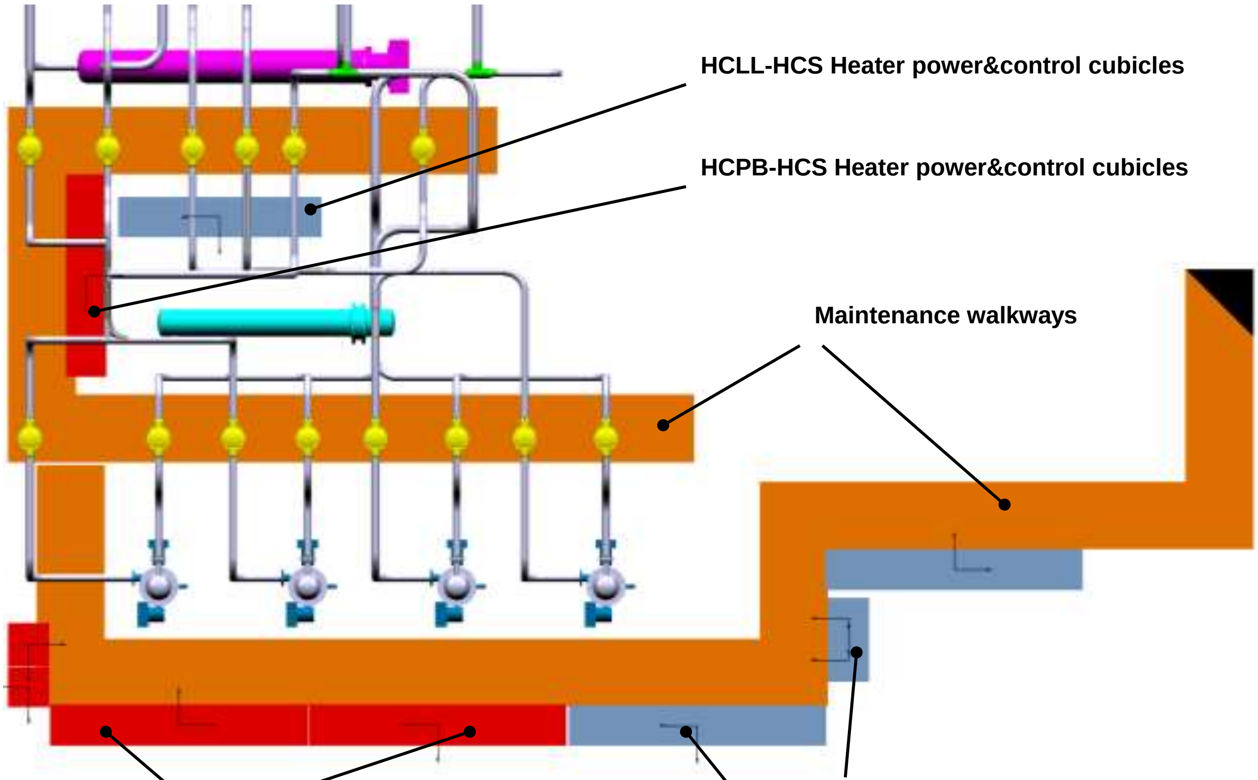

Figure 4.6 New exploratory arrangement for cubicles and walkways in "CVCS area"

To save space, the electrical heaters have been arranged one on top of another one (see Figure 4.7).

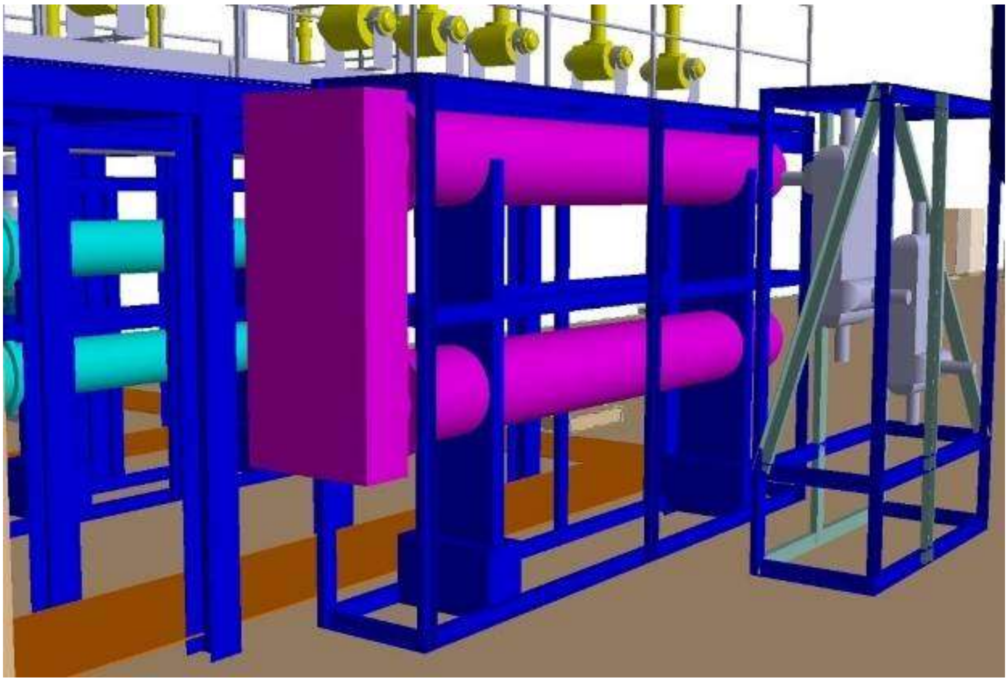

Figure 4.7 Arrangement of the two heaters

Proper walkways allow maintenance personnel to easily reach any equipment. Moreover, CATIA "Human Builder" has been used to check for accessibility of filters and flanges in more detail.

At the current stage, HCPB and HCLL HCSs contain 14 DN100 servo-actuated valves, which are heavy and quite bulky. For this reason, a further steel platform has been provided at about 3000mm from the floor of CVCS area, which should hold all the valves and allow their maintenance (see Figure 4.8).

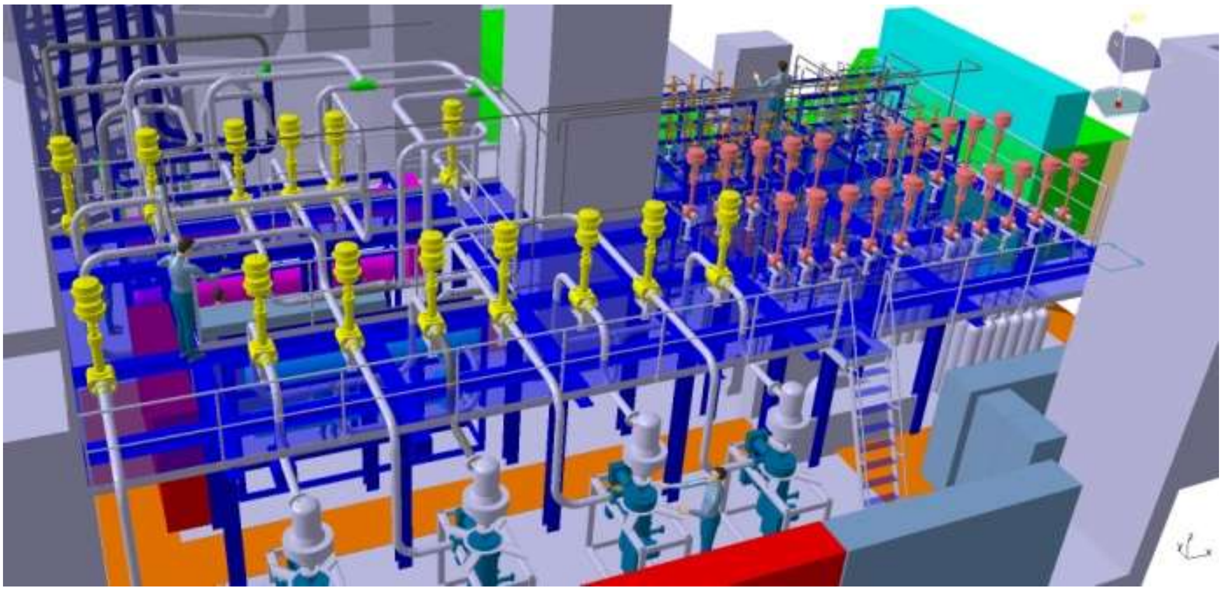

Figure 4.8 Steel platform supporting valves in CVCS area

That choice guarantees more space at floor level for heavy equipment and maintenance walkways.

Concerning DN100 piping, in the first place, 5D bent pipes have been preferred against welded elbows. However, it is worth noticing that the final choice between the two possible solutions will require a proper cost analysis.

The length of pipes also consider the space needed by in-line instrumentations, such as flow meters (not provided), as reported in the corresponding Process and Instrumentation Diagram (P&ID).

With reference to PCSs, as aforementioned, they have been located in another zone of CVCS area. In order to guarantee the maintainability of the two diaphragm compressors and the buffer tanks, DN40 valves have been placed on the same steel platform used for DN100 valves.

4.4 Piping layout design of CPS

The Coolant Purification System (CPS) is one of the main ancillary circuits (or "sub-systems") of HCLL and HCPB TBS to be tested in ITER. The CPS, for both the European TBM concepts (HCLL and HCPB), has the role to extract the permeated tritium from the primary circuit, keeping controlled the HCS chemistry [3].

Since the two sub-systems are identical, just one process loop is described here.

The piping selected for CPS is DN25. 3D bends have been chosen for pipes according to *ITER piping design guidelines* [4].

With reference to the design, the main equipment has been grouped by function and each group has been located in a dedicated area (see Figure 4.9). As for the main loop of the two HCS, valves and light components have been located on the top platform to gain the space for the heavy components and to reduce the loads on the secondary structures. Moreover, all the aspects related to the accessibility and maintainability, known at the present design stage, have been carefully considered.

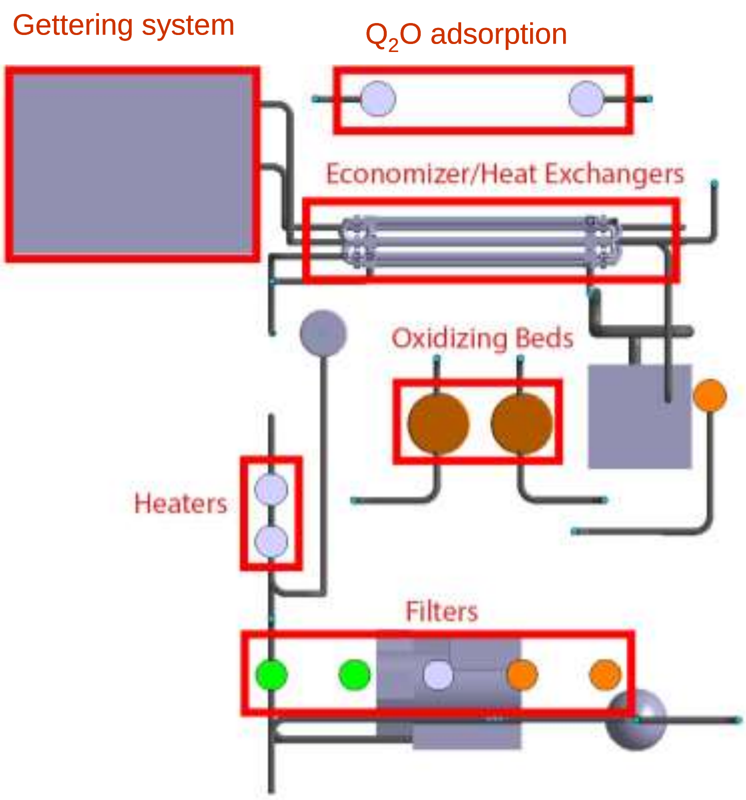

Figure 4.9 Schematic layout of CPS

The layout of both systems (HCPB and HCLL CPSs) is almost symmetric with respect to the Heated Getters, which have been provided as black-boxes.

One of the two boxes is at the floor level of the CVCS Area, while the other is located on the steel platform at the upper level.

Two maintenance walkways have been provided for each CPS to serve the equipment located at the floor level.

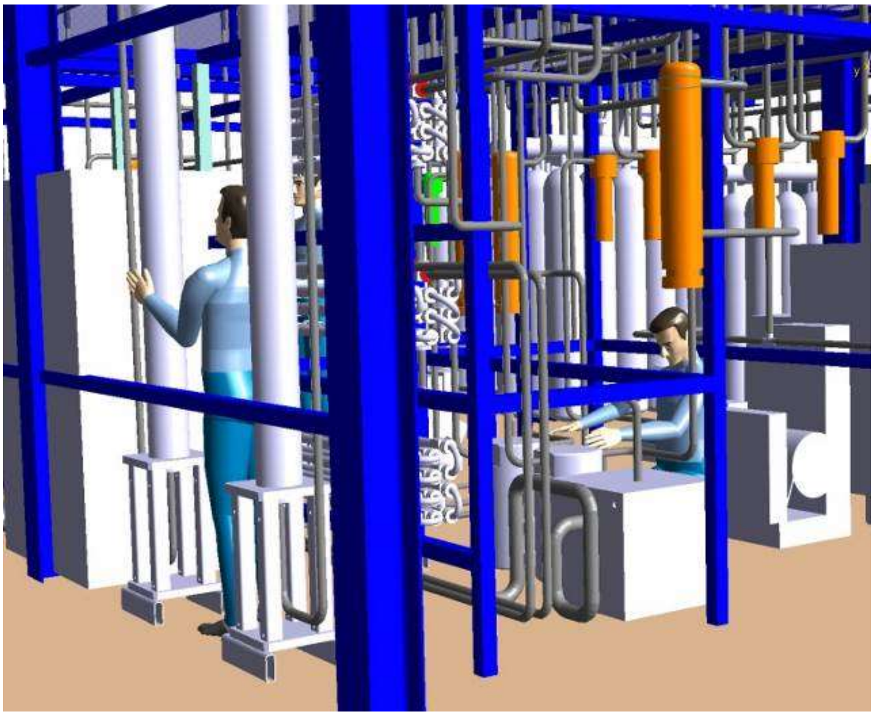

Figure 4.10 Maintenance walkways for Q2O adsorbers and oxidizing bed

In particular, the one allows reaching both the Q_2O adsorbers and the Heat Exchangers, while the other provides the accessibility to the filters, the oxidizing beds, the air cooler and the circulator (see Figure 4.10).

The filters are placed at eye level to make easy their inspection, mounting and maintaining.

A further maintenance walkway has been provided between two CPSs, both on the upper (i.e. the steel platform) and on the lower level (i.e. the "CVCS Area" floor). The maintenance activities have been also simulated.

4.5 Supporting steel frames in "CVCS Area"

Every component of a piping system must be supported not only against its own weight, but also with respect to other possible sources of stress (e.g. thermal stress, seismic loads, etc.).

However, it should be noticed that, at the present conceptual design stage, only the preliminary design of supporting steel frames, according to applicable standards, was requested. Therefore no detailed models of any bond (such as hangers, anchors, supports, etc.) between steel structures and actual equipment, pipes, valves or in-line instruments have been provided. More accurate analyses will be able to be done only when these major details are defined.

With reference to the heavy equipment (such as circulators, heaters, exchangers, etc.), each of them has been provided with its own steel frame to be anchored in the reinforced concrete floor of "CVCS Area" by means of proper embedded plates.

On the other hand, the valves have been placed on a steel secondary platform which can be accessed by means of two service stairs (see Figure 4.11).

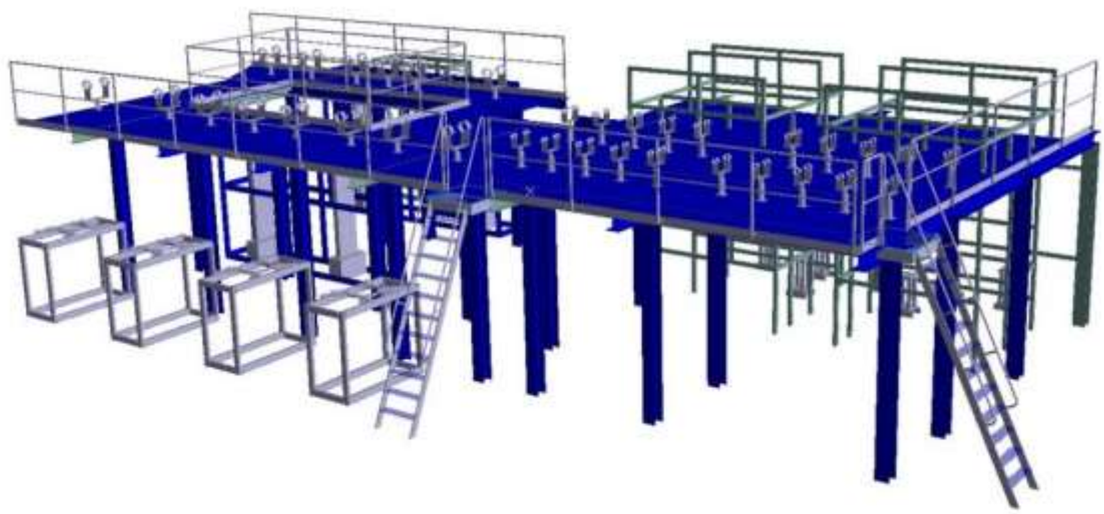

Figure 4.11 Steel structures in CVCS Area.

Given the weight of the valves and the corresponding piping, the appraisal load that the platform shall bear has been evaluated in about 1500kg/m^2. This value includes a safety factor of 2. The same platform has some openings (highlighted in red in Figure 4.12) allowing the possible installation of heavy equipment (such as heaters, heat exchangers and compressors) by means of a crane.

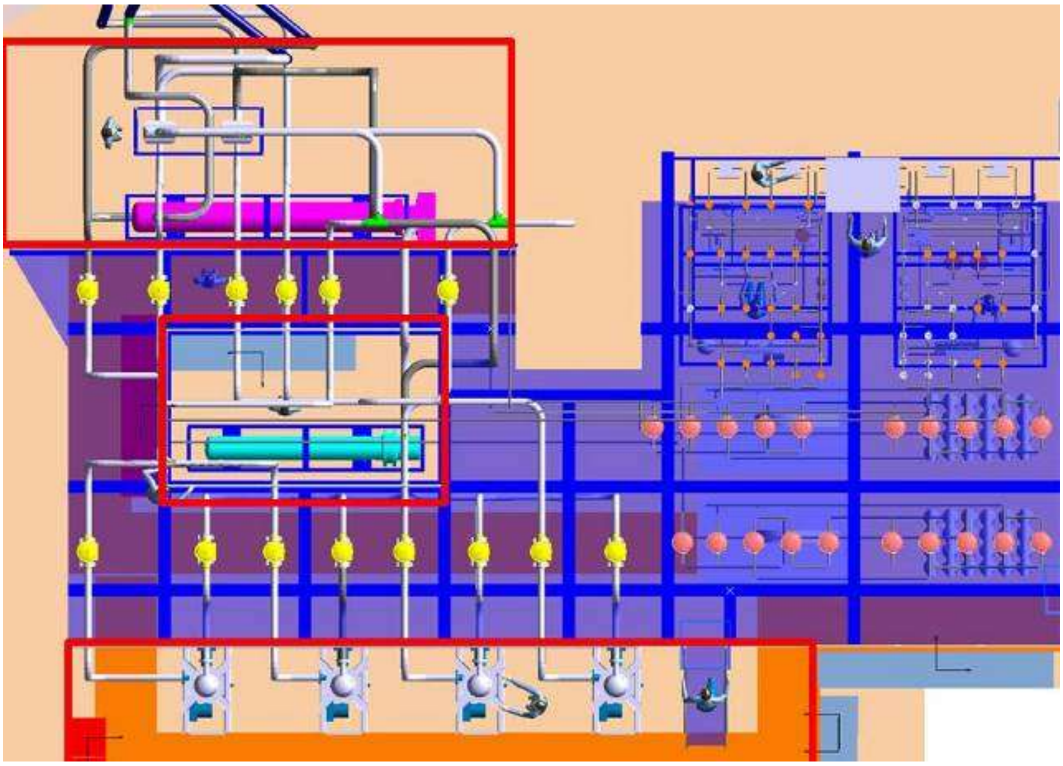

Figure 4.12 Horizontal openings in the steel platform

In order to check for accessibility of the equipment at the floor level with *Human Builder*, an exploratory arrangement for beams and pillars which should support that platform has been also provided.

However, this choice should not be intended as binding, since the corresponding steel plates embedded in the reinforced concrete floor of "CVCS Area" (so-called embedded plates), which are necessary to support those pillars, have not been considered. Therefore this point needs further analysis.

4.6 Conclusions and future work

The present work showed that VR engineering tools turned out very useful to define a suitable arrangement for equipment and piping lines in "CVCS Area".

More specifically, *Digital Human Model* has shown its usefulness in investigating accessibility of equipment and systems from the preliminary stages of piping design. In some cases, the simulations have resulted in changes in the initial space reservations.

Heavy components, such as circulators, heaters, heat-exchangers, etc, have been placed at ground level to make it easier their inspection and their possible moving for maintenance. On the other hand, in-line elements, such as valves and space reservation for flow-meters, have been placed at height, on a proper steel platform.

As mentioned, at the current stage of design, details of supports and hangers for equipment, pipes and in-line elements have not been considered. In particular, mounting sequences can be defined only when all the latter details will have been finalized. Therefore, future work could be focused on using process simulation software in virtual environment to check for actual feasibility and possible human safety issues related to the assembly and maintenance procedures of the piping system [10].

4.7 References

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Chapter 5 *Industrial application: Design Validation of International Fusion Materials Irradiation Facility (IFMIF) remote maintenance tools*

5.1 Introduction

The International Fusion Materials Irradiation Facility (IFMIF) will be used to study the properties of materials for future fusion reactors. In particular, IFMIF will test the behavior of radiation-resistant or low-activation materials up to a cumulative dose of 100 dpa by neutron damage in 5 years.

It is part of the project on nuclear fusion in the frame of the agreement between Europe and Japan as part of the Broader Approach Agreement. In this context, ENEA is responsible, among other things, for the design of the Target Assembly (TA) and the study and the validation of maintenance activities needed to recondition the target itself.

The activities described in the following sections concern the validation of the maintenance procedures of the TA. The work was developed in collaboration with ENEA Brasimone Research Centre.

In particular, the TA of IFMIF is a lithium target that produces the proper high-energy neutron flux (14 MeV) needed to test materials, via the stripping reaction D^+-Li. The environment in which this component will operate is considered critical both during the operational phase due to irradiation of materials and also during the shut-down phase for preventive maintenance.

The gamma dose during the maintenance phase in the target area is expected to reach some kGy/h. It is clear that these values of gamma activity make any manual maintenance operation impossible. Thus, the only alternative is remote maintenance.

All procedures of remote maintenance must be validated experimentally and optimized on full-scale prototypes of both the target and the environment in which it will operate.

In this chapter will be describes the digital simulations conducted to optimize and reduce the number of interventions needed on TA.

The main objectives the work were the creation of 3D models of the RH tools that were still missing, the preparation of the workspace layout (DRP, *Divertor Test Platform*), the simulation and the optimization of the maintenance procedures and, eventually, an estimation of the expected maintenance time (Figure 5.1).

In the following subsections the activities conducted are being discussed in more detail.

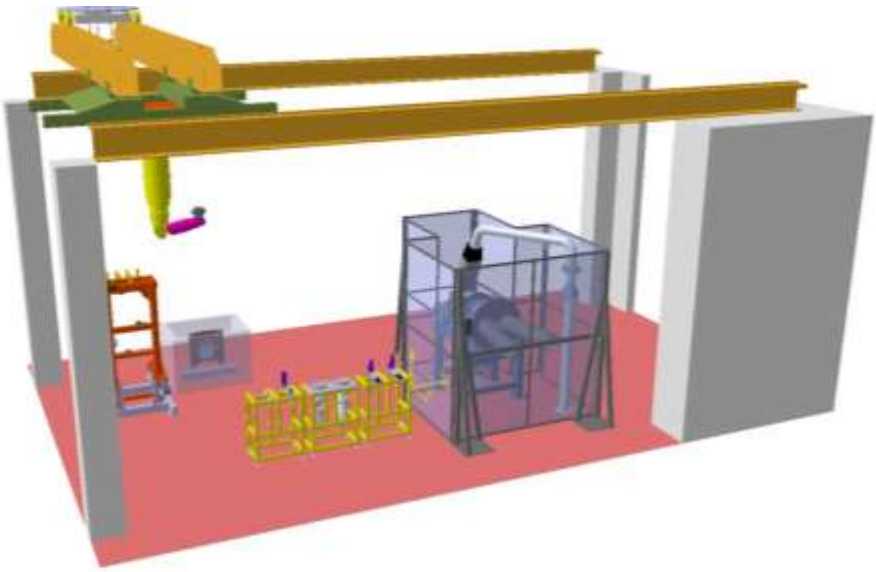

Figure 5.1 DRP with all pieces of equipment

5.2 Modelling of Remote Maintenance Tools in VR environment

As aforementioned, the very first step in order to conduct the digital simulations has been the 3D modelling of the tools that was missing, starting from technical documentation [1] provided by ENEA. Afterwards, each digital tool has been provided with a kinematic model.

CATIA and DELMIA V5 by Dassault Systemes have been used for 3D modelling and kinematics of the digital tools respectively.

It is worth noticing that 3D models should be intended just as digital representations for simulation purposes (*conceptual models*) and not as engineering drawings.

Each kinematic constraint has been modelled according to technical documentation for every component of DRP.

In particular, the following objects have been modelled:

- ✓ *Angle screwing device*
- ✓ *Straight screwing device*
- ✓ *Plasma Facing Components Transporter*
- ✓ *Support and storage system for screwing devices and cleaning tool*
- ✓ *Storage system for Back-plate*
- ✓ *Kinematic model of lightweight robotic arm ;*
- ✓ *Kinematic model of Crane and telescopic arm;*

5.2.1. *Angle screwing device*

The angle screwing device is actually made by Ober SRL and it includes a control cubicle along with the angle transmission system. The control cubicle has not been modelled as it is not involved in digital simulations.

Starting from the technical characteristics shown in Figure 5.1, and the overall dimensions (see Figure 5.2) provided by ENEA[1], a 3D Bottom-Up approach has been used to model the transmission, the screwing device, and the end-effector interface. Afterwards, the whole subsystem has been assembled with CATIA "*Assembly Design*".

Table 5.1 Technical characteristics of the angle screwing device

Maximum Torque	80 [Nm]
Nominal Torque	40 [Nm]
Rotation Speed	1÷250 [rpm]

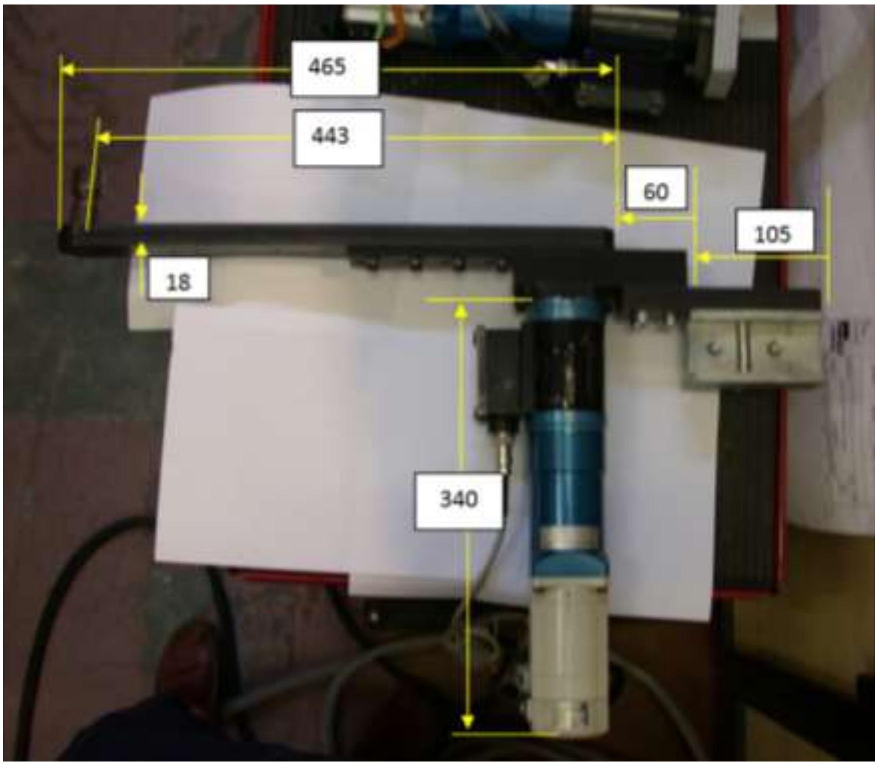

Figure 5.2 Overall dimensions of the angle screwing device

Afterwards, each kinematic joint has been defined for the assembly. In particular, a revolute joint between the socket wrench and the transmission arm has been provided (see Figure 5.3). It is understood that this joint is used to simulate the fastening of nuts and screws.

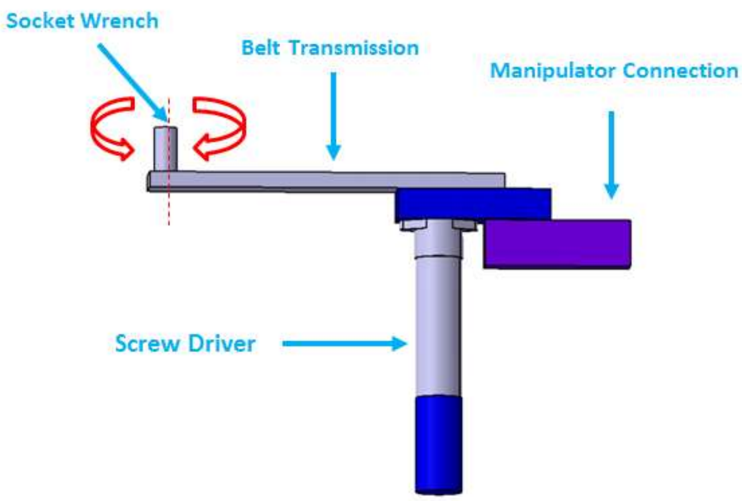

Figure 5.3 3D model of the angle screwing device

This tool will be mainly used to open/close the *Fast Disconnecting System (FDS)* that is on the exit channel of TA, as well as to control the bellows that envelopes the beam duct, and to release the safety bolts that hold the TA in position.

5.2.2. *Straight screwing device*

The actual straight screwing device will be provided by Ober SRL. As in the case of the angle screwing device, the 3D model has been developed according to the technical data provided by ENEA [1] (see Figure 5.2 and Figure 5.4).

Table 5.2 Technical characteristis id angle screwdriver

Maximum Torque	150 Nm
Torque Precision	3%
Rotational Speed	1÷250 rpm
Torque and angle controlled	

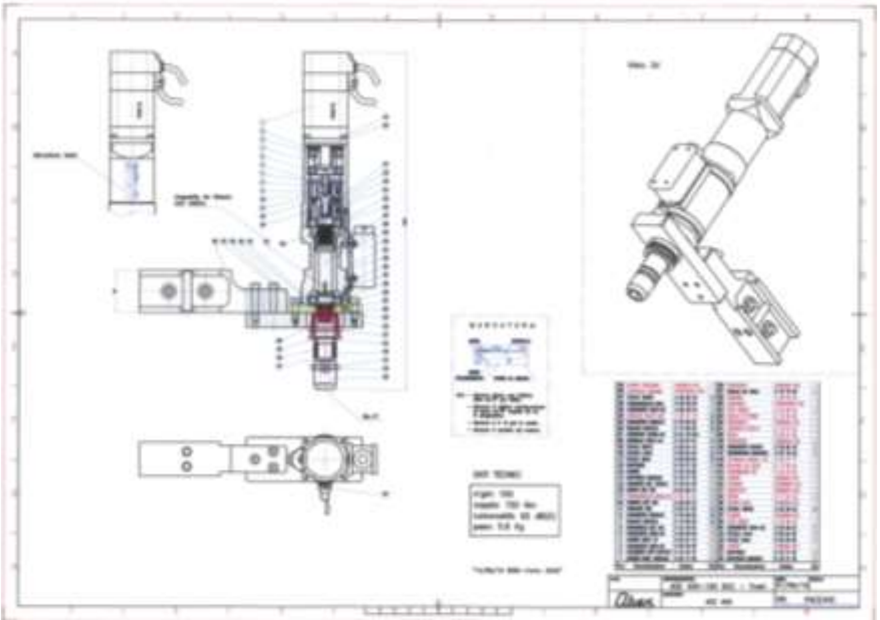

Figure 5.4 . Assembly drawing of straight screwing device

Again, a revolute joint has been provided between the socket wrench and the mandrel of the screwing device (see Figure 5.5). This tool will be mainly used to fasten the Back-Plate (BP) and the inlet part of the TA.

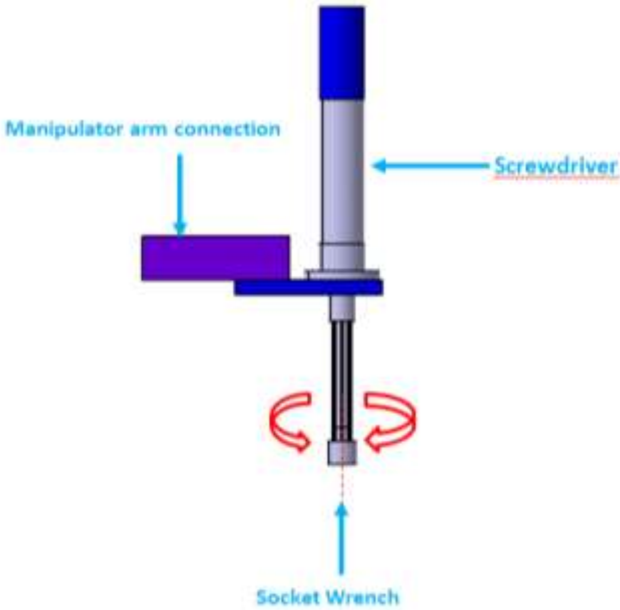

Figure 5.5 3D model of straight screwing device

5.2.3. *Plasma Facing Components Transporter*

The *Plasma Facing Components Transporter* (PFCT) is a device designed to put the TA in the correct position, as well as to replace it. PFCT indeed provides the further degrees of freedom (DoF) needed to properly align the component in the space, given that the crane is a Cartesian machine without revolute joints.

Thus the PFCT is designed as a 6-DoF machine with a load capacity of 5 tons with yet a good accuracy at the design speed range.

The PFCT is installed on the same axis of the main robot arm cart and uses three winches mounted at 120° on the rotating wheel.

Each winch can be driven in sync with the others or even independently in order to have both the translation along Z axis and the rotation around the other axes.

The reference technical data are shown in Figure 5.3. Starting from the 2D drawing by ENEA (see Figure 5.6), the main components have been modelled in 3D and then assembled.

Table 5.3 Technical characteristic of PFTC

Degrees of freedom	6
Maximum load	5 tons
Single wire maximum load	2 tons
Working Area	10,500m x 3,2x 5 m

Range rotation Z axis	0-90°
Range rotation X, Y axis	±25°
Repeatability	≤±0.25mm
X axis Speed Translation	0.3–30 mm/s
Y axis Speed Translation	0.3–30 mm/s
Z axis Speed Translation	0.3–30 mm/s
X axis Speed Rotation	0,1-1 mm/s
Y axis Speed Rotation	0,1-1 mm/s
Z axis Speed Rotation	0,1-1 mm/s

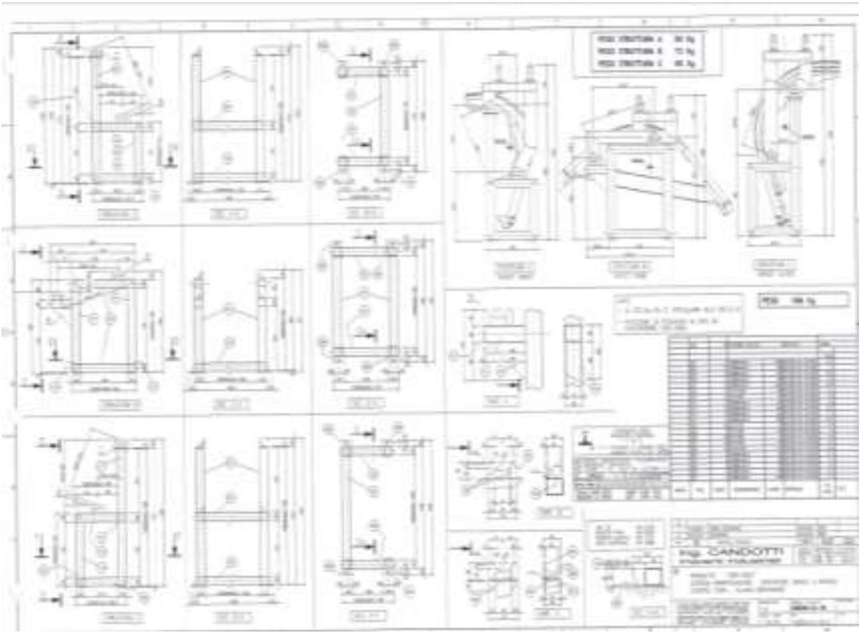

Figure 5.6 PFTC 2d drawing

A prismatic joint has been provided between the axis of the cart and the axis of the crane (namely, X axis in Figure 5.7).

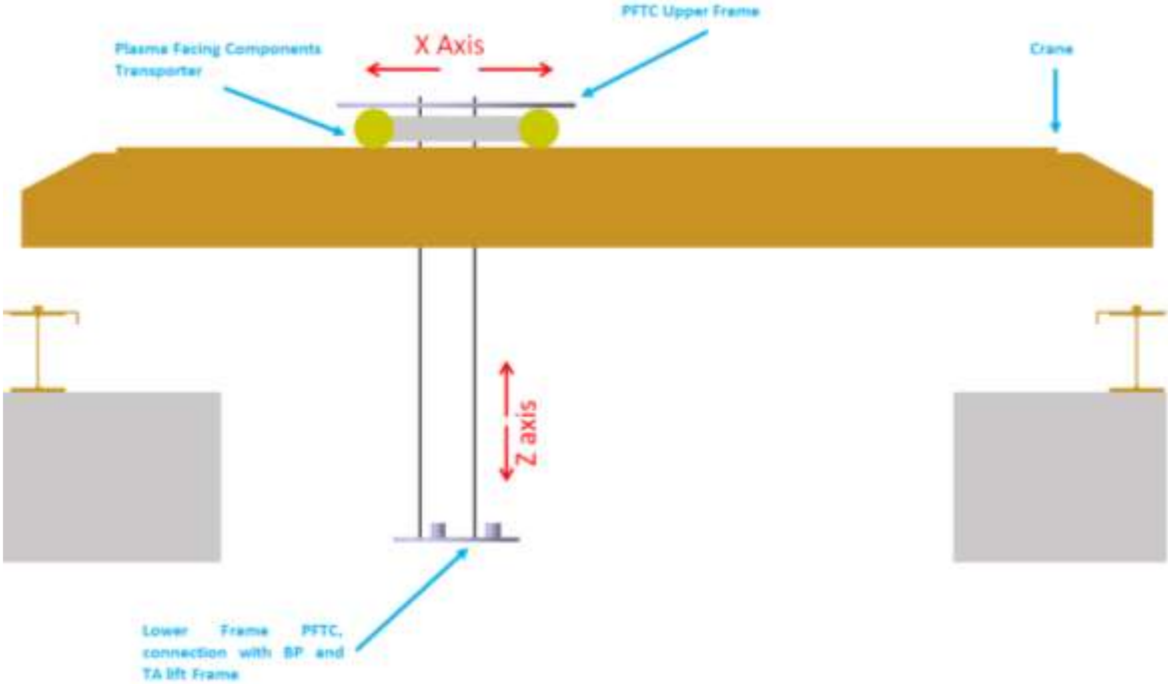

Figure 5.7 3d model of Plasma Facing Components Transporter

Translation along Z axis (see Figure 5.7) is guaranteed by another prismatic joint between upper plate and lower plate. Eventually, rotations of the lower plate have been modelled using one spherical joint (see Figure 5.8).

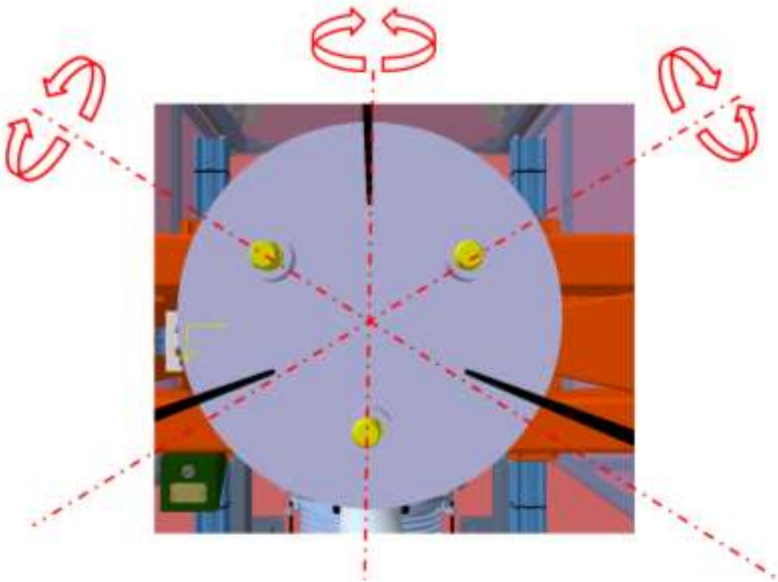

Figure 5.8 Rotational Axis lower plate of PFTC

5.2.4. *Support and storage system for screwing devices and cleaning tools*

The 3D models of the supports for the screwing devices (both the straight and the angle one) are shown in Figure 5.9.

The framework is designed to support the screwing devices in vertical position with their attaching interface facing the manipulator arm. (see Figure 5.10). This choice helps the control of the robot by reducing the movements needed to catch tools.

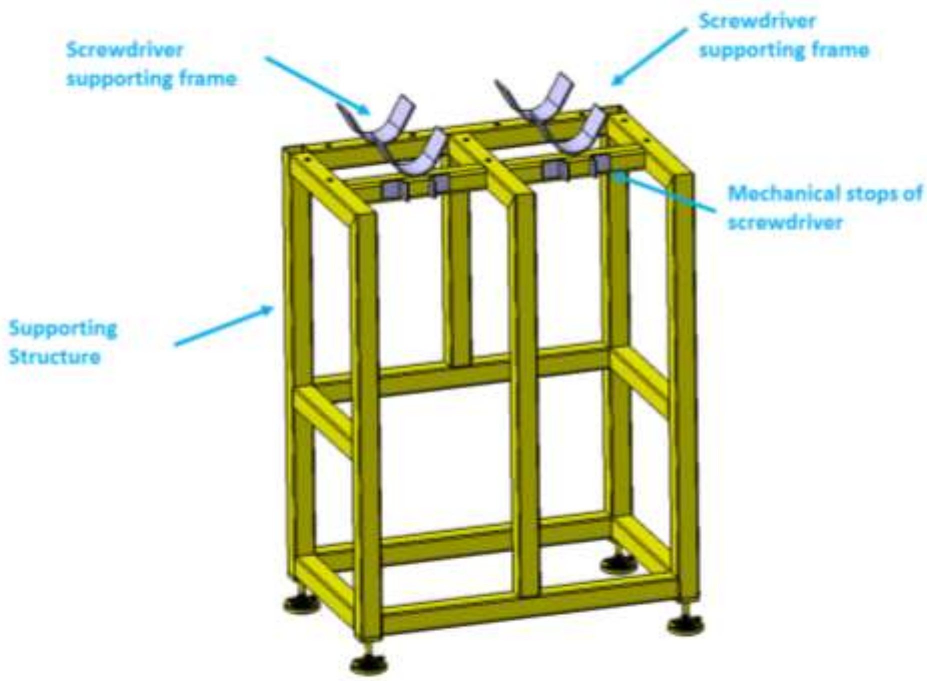

Figure 5.9 Angular and straight screwdriver supporting frame

Thus, the support is provided with a proper saddle to house screwing devices body as well as proper rails that keep the tools in vertical position (see Figure 5.10).

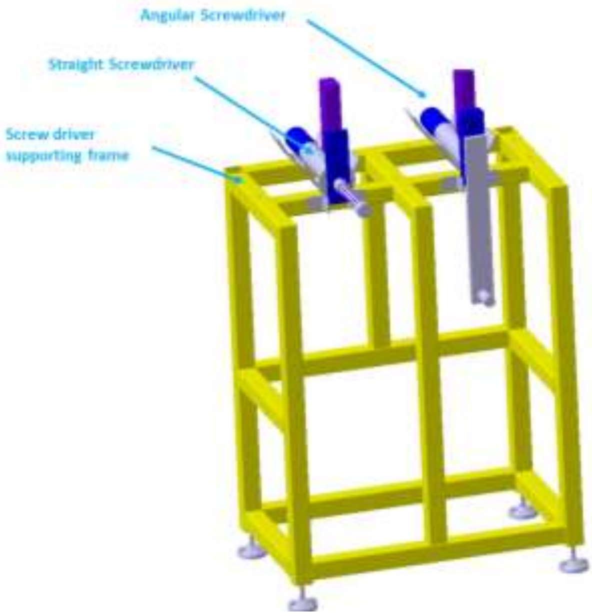

Figure 5.10 3d model of screwdrivers storage system

Support and storage system for Cleaning Tools system is shown in Figure 5.11. Even in this case, the framework is designed to hold tools in vertical position.

It is worth noticing that the 3D model of the cleaning tool provided by ENEA was lacking of any attaching interface, which has been consequently modelled.

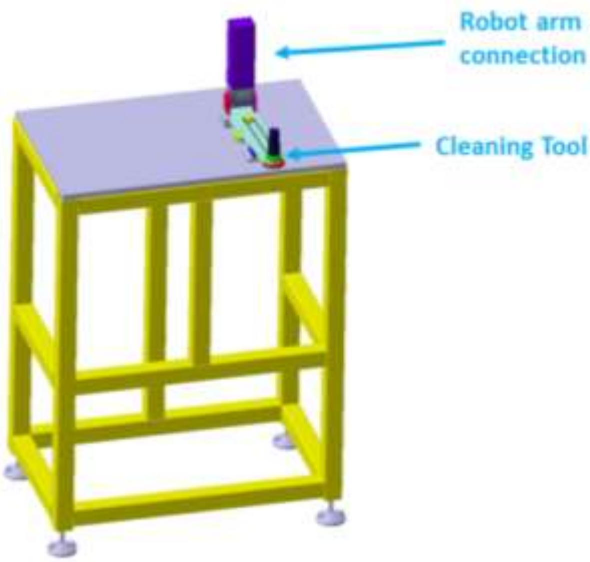

Figure 5.11 Cleaning Tools Storage System

5.2.5. *Storage system for Back-plate (BP)*

In order to remove the BP from the workspace after the disassembly of the TA, a proper cassette to contain the BP and hold it in vertical position has been modelled (see Figure 5.12).

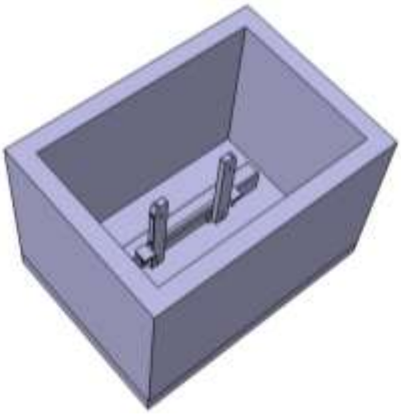

Figure 5.12 3D model of BP storage box

The storage box has a rail system inside that houses the BP and hold it in vertical position (see Figure 5.13).

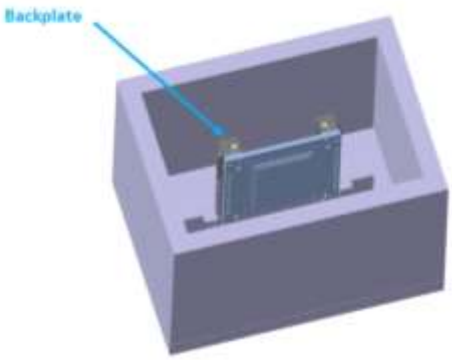

Figure 5.13 BP storage system

5.2.6. *Kinematic model for lightweight robotic arm*

The 3D models of lightweight robot have been provided by ENEA, but they were lacking of any kinematic model. Starting from the technical data (Table 5.4) and 2D drawings (Figure 5.14) and 3D models of the robotic arm (Figure 5.15), kinematic joints for the lightweight robot have been implemented with DELMIA as shown in Figure 5.15.

Table 5.4 Technical Characteristic of lightweight robotic arm

Maximum load	15 kg
Degrees of freedom	4
Range of rotation first joint	± 130°
Range of rotation second joint	± 135°
Range of rotation third joint	± 115°
Range rotation fourth joint	:± 150°
Speed of rotation first joint	50°/s
Rd Speed of rotation second joint	50°/s
Speed of rotation third joint	50°/s
Speed of rotation fourth joint	50°/s

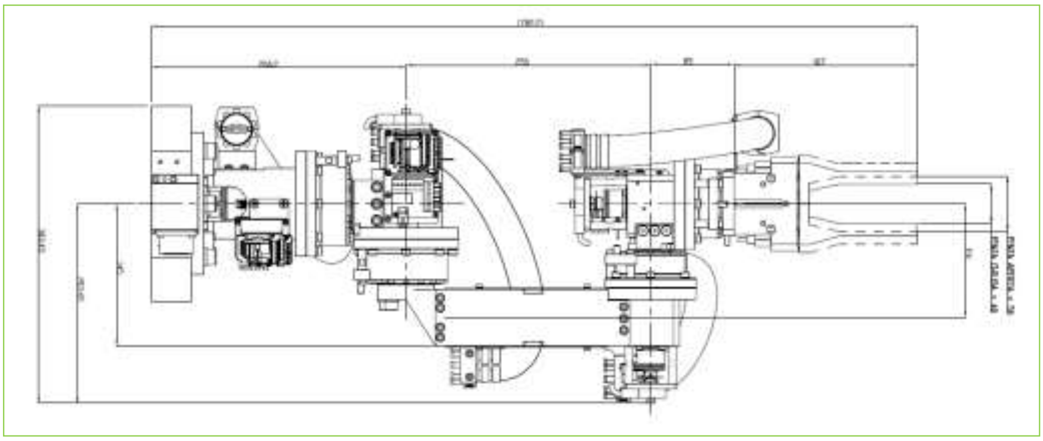

Figure 5.14 Overall dimensions of lightweight robotic arm

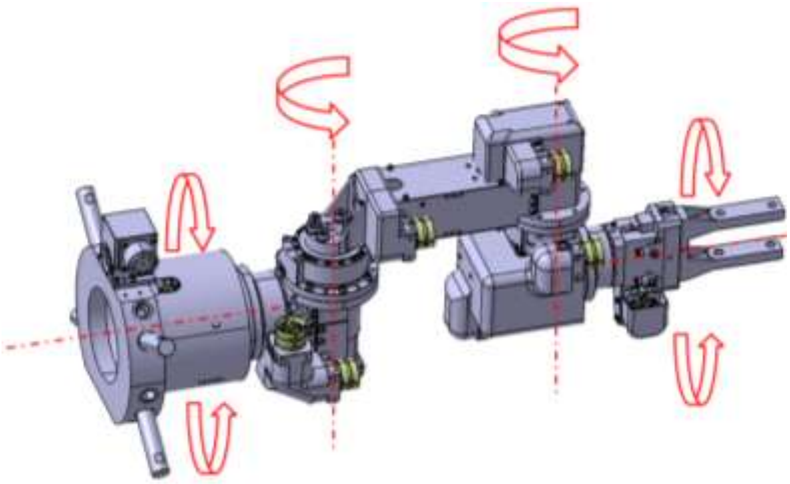

Figure 5.15 3d model of lightweight robotic arm with kinematic joints

5.2.7. *Kinematic model for crane and telescopic arm*

As shown in Figure 5.1 DRP workspace includes:

- ✓ a crane: load capacity: 5 tons, length: 10.5 m, width: 5m, height: 5.15 m;
- ✓ a telescopic arm installed on a carriage that slides along X axis of the crane,
- ✓ PFTC installed on the upper part of the supporting beam of the crane (see Figure 5.7 and Figure 5.16)

The 3D models provided by ENEA have been slightly modified to better simulate the actual functionalities of the manipulator. In particular, some telescopic extensions have been added along with a CGS flange to the robot head (see Figure 5.17).

Therefore, a complete kinematic model for the crane has been defined with CATIA "*Device Building*".

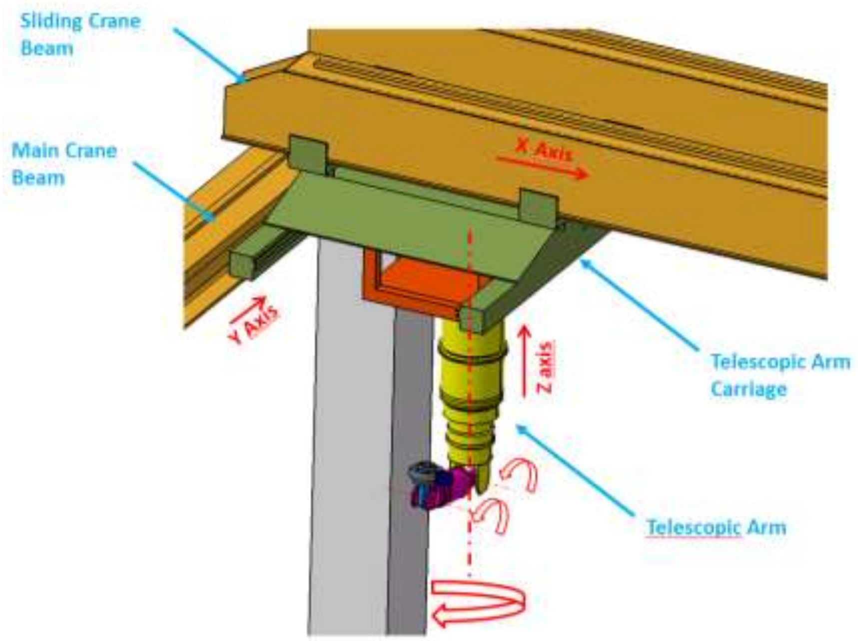

Figure 5.16 Axis of kinematic joint of Crane

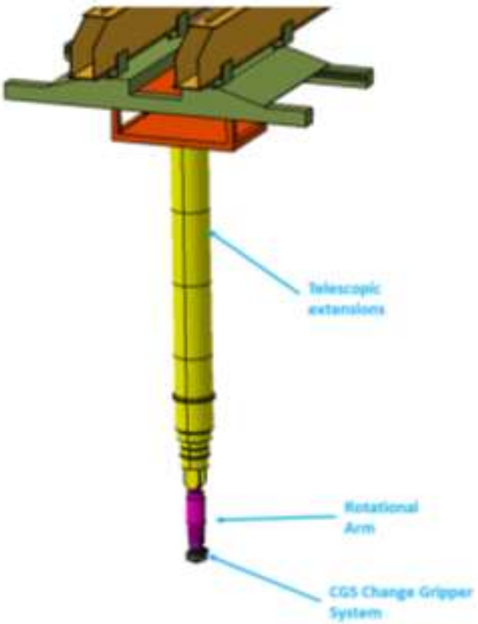

Figure 5.17 Telescopic arm extended

5.3 Study and optimization of maintenance procedures of the TA in virtual environment

According to the technical requirements, maintenance simulations of the TA focused on two different scenarios have been developed [1]. In a first case, only the BP is replaced, while the TA is just refurbished. In a second case, the whole TA is replaced, while the attaching flanges are refurbished.

In order to go on with the maintenance simulations, several design environment of DELMIA has been used (namely, "*Assembly Process Simulation*", "*Workcell Sequencing*" e "*Device Task Definition*").

In particular, the sub-tasks for each piece of equipment involved in the maintenance task have been defined with "*Device Task Definition*" module, while the work sequences have been detailed with the "*Workcell Sequencing*" environment. Eventually, the whole task has been simulated with "*Assembly Process Simulation"* module.

Starting from the outcomes of development stages described in the preceding paragraphs, the work-cell layout has been defined.

The main objectives were:

- ✓ minimizing the residence time of the equipment inside the Test Cell
- ✓ minimizing the number of movements of each device during the maintenance activity

The PFCT is installed on top of the crane and can translate along X axis (Figure 5.7). A telescopic arm is also mounted on the same crane which can slide in the same direction; this feature could raise interference issues during manipulation of the components. For this, the components to be handled by different tools (namely the PFTC and the telescopic arm) have been located in two different areas with respect to the sliding crane beam (see Figure 5.16,Figure 5.18 and Figure 5.19).

The tools aimed at manipulating the BP and the TA and the BP storage cassette are located on the same side, while the equipment to be manipulated by the telescopic arm has been positioned on the opposite side (down in Figure 5.18).

On the one hand, this configuration limits the movements needed for each component, and on the other hand, avoids possible interferences between PFTC and telescopic arm.

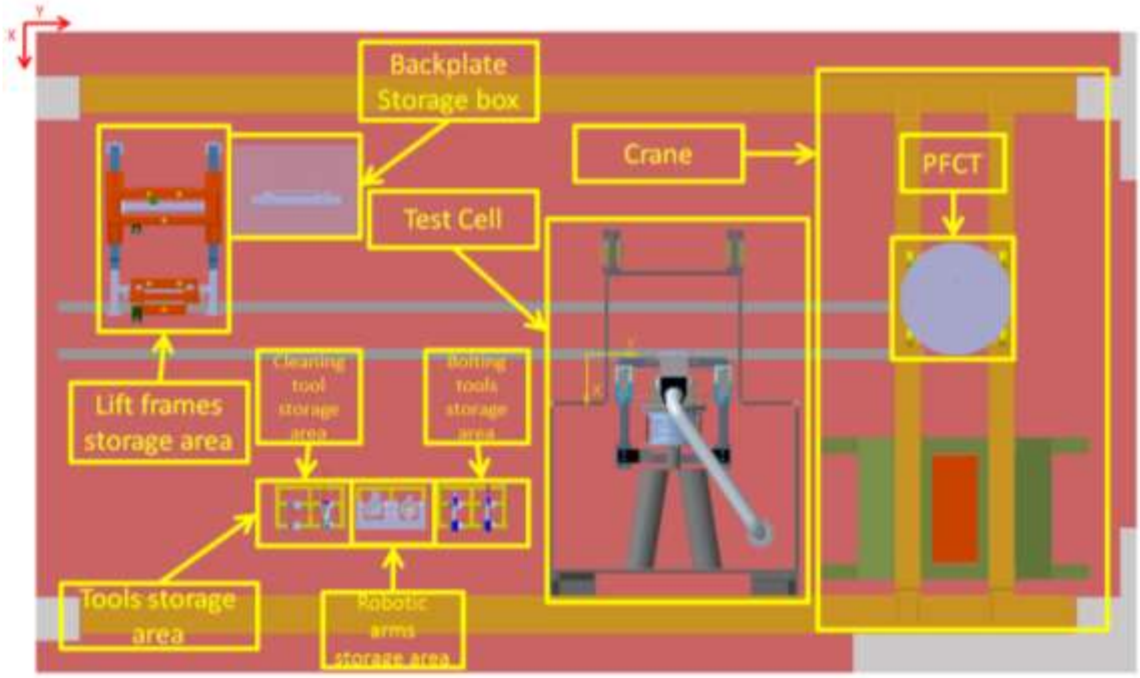

Figure 5.18 DRP Layout

As shown in Figure 5.19, the crane in its rest position is next to the tools to be manipulated. In particular, as we can note that the PFCT in its rest position is above the lifting system of the BP and the TA, while the manipulator is near the storage areas of the cleaning tools and the screwing devices.

When the crane approaches the Test Cell, the manipulator first passes over the storage area of robotic arms and then reaches the storage area of the maintenance tools. This also reduces the movements of the robotic cell.

It should be noted that the development and the optimization of the layout of the entire area was carried out in parallel to the development of the simulation activities that involved also various-skilled personnel, according to the *concurrent engineering* philosophy [4].

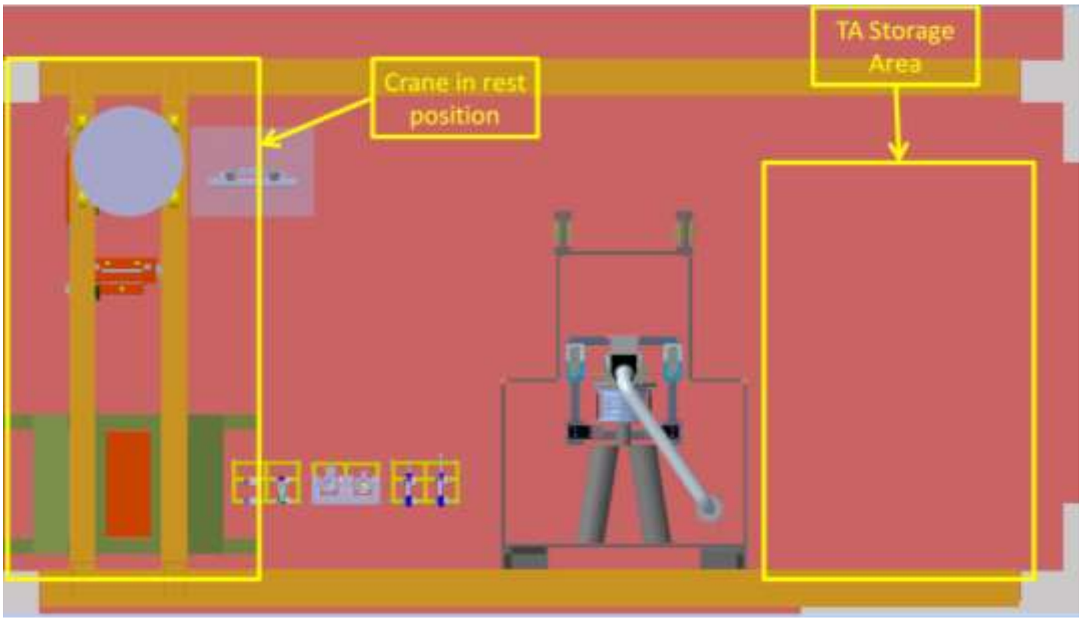

Figure 5.19 DRP Layout

Thus, the procedures for replacing the BP and the whole TA have been simulated.

The digital simulations have been used for a first estimation of the time needed for each operation [5].

5.3.1. *Replacement of the Back Plate and Target refurbishment*

The replacement of the BP is conducted within the TC. Both the removal and the installation of the BP imply the use of the screwing devices and the robotic arm installed on the telescopic crane. One of the most time-expensive operations is the fastening of the bolts on the front side of the BP and of the rails needed for its installation. Indeed, the rated torque has to be attained in 5 steps (20% increment each step).

The tightening torque to be applied to the bolts and the two rails for an optimal sealing is about 26 Nm.

The activity at issue was entirely simulated in a virtual environment. Once paths workflows were defined, according to the technical specifications, each task has been assigned with its duration.

Then, the digital simulations were saved as a movie (Figure 5.20, Figure 5.21 and Figure 5.22).

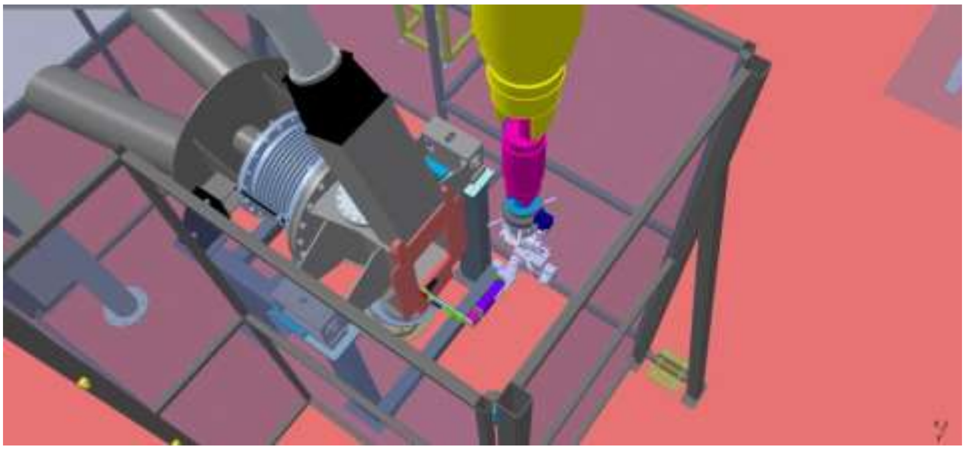

Figure 5.20 Cleaning of Back Plate supporting plate

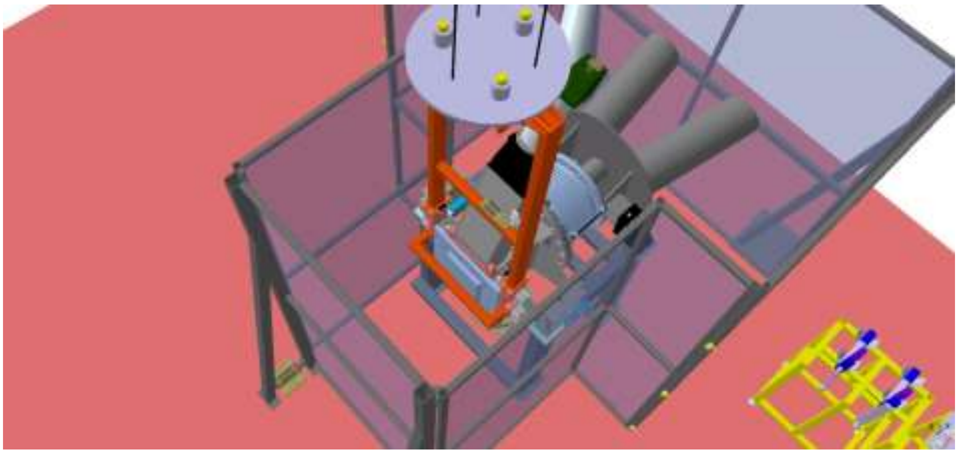

Figure 5.21 Back plate mounting

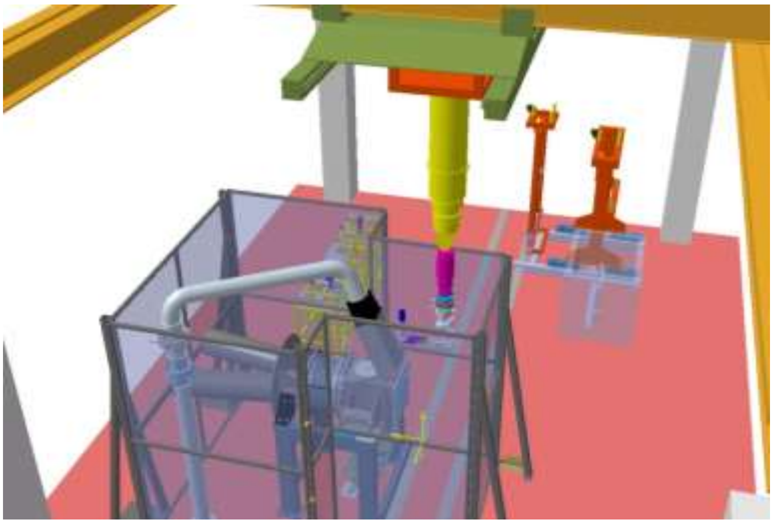

Figure 5.22 Back Plate Fastening

Replacement of the Target

The TA is replaced by moving the target in the vertical direction, first upwards and then downwards. To allow the lifting of the TA in the vertical direction, the beam duct of TA is endowed with a compactable bellows. It frees the movable flange on the beam side from the external profile of the FDS. The bellows can be compacted up to 120mm [1].

As in the previous case, the whole replacement activity has been simulated and a reference time has been assigned to each sub-tasks (see Figure 5.23).

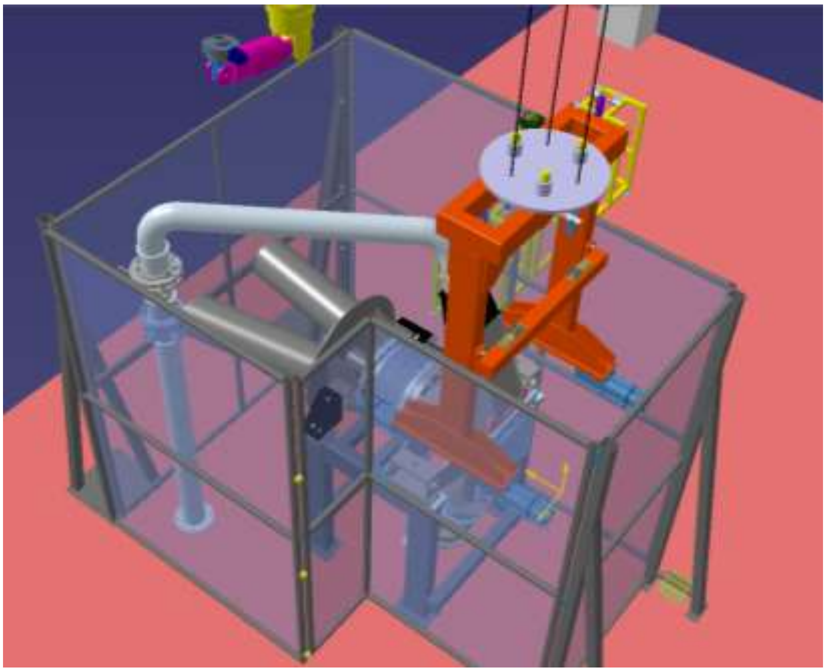

Figure 5.23 TA refurbishment

3.2 Maintenance time for each operation and total residence time of the devices inside the TC

The digital simulation provided a preliminary estimate of the time needed for each activity and, in particular, for each single movement. The work paths of all devices involved in the maintenance activity have been defined with DELMIA.

Afterwards, given the technical characteristics of all the components, the time needed for each sub-task has been estimated considering that the speed of the devices had to be maximized during the transfer movements from gripping points to workspace, and reduced during insert operations (Figure 5.24).

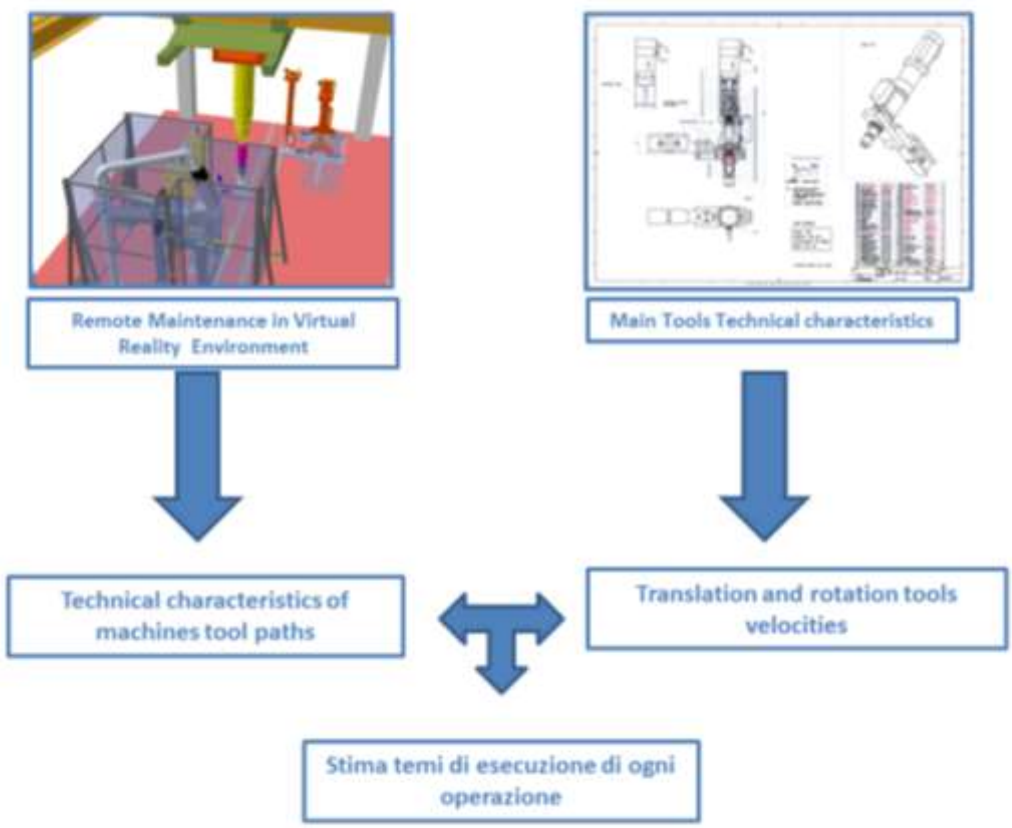

Figure 5.24 Methodology used to estimate the maintenance time

The Figure 5.24summarizes the methodology used for the determination of the timing for each operation. Tables 5 and 6 contain the list of operations of maintenance activities along with the related execution time. The residence times of the tools within the TC are highlighted in yellow.

Table 5.5 Maintenance time fro Back Plate Refurbishment

BACKPLATE REMOVAL	
Operation	Average Time (h:min:s)
Overhead crane in rest position (START)	0
Pick up the 7 DoF RBT	00:05:15
Take BT	00:04:45
Move the overhead crane above the TC	00:02:00
Deploy the RBT inside the TC	00:02:15
Unlock the Skates	00:10:30
Unlock the bolts on the BP	00:46:45
Detach the BP	00:15:15
Extract the RBT from TC	00:02:15
Back the overhead crane to the RBT docking station	00:02:45
Release the BT	00:02:00
Release the RBT	00:05:00
Move the overhead crane to the BP gripper	0:1:00
Pick up the BP gripper	0:4:45
Move the overhead crane above the TC	0:2:45
Deploy and align the BP gripper in the TC	0:4:45
Dock the BP	0:5:00
Extract the BP up to above the interface frame	0:4:00
Extract the BP from the TC	0:2:00
Transfer the old BP in the hot cell (not included in the simulation)	0:04:00
Release the BP on its storage support (not included in the simulation)	0:04:00
Back the overhead crane from hot cell (not included in the simulation)	0:04:00
Release the BP gripper	0:05:45
Cleaning of the Frame	
Pick up the 7 DoF RBT	0:05:00
Take the cleaning tool	0:05:00
Move the overhead crane above the TC	0:02:00
Deploy the RBT inside the TC	0:02:00
Clean the interface frame of the BP	2:30:00
Extract the RBT from the TC	0:02:00
Back the overhead crane to RBT docking station	0:02:00
Release the CT	0:02:00
Release the RBT	0:02:00
BACKPLATE INSTALLATION	
Move the overhead crane to the BP gripper station	0:01:00
Pick up the BP gripper	0:05:30
Move the overhead crane to the hot cell (not included in the simulation)	0:04:00
Grasp the BP	0:07:45
Back the overhead crane from the hot cell (not included in	0:04:00

the simulation)	
Deploy and align the BP gripper in the TC	0:12:00
Align and insert the BP	0:17:15
Release the BP gripper	0:02:00
Extract the BP gripper from the TC	0:03:45
Back the overhead crane to storage area	0:03:30
Release the BP gripper on its support;	0:05:45
Dock the 7 DoF RBT	0:05:30
Take the BT	0:05:30
Move the Overhead crane above the TC	0:02:30
Deploy the RBT inside TC	0:02:45
Loop: tighten skates and bolts of the BP to 20% each step up to 100%	4:32:00
Extract the RBT from TC	0:02:15
Back the overhead crane to RBT docking station	0:03:15
Release the Bolting tool	0:04:00
Release the RBT	0:06:45
Back the Overhead crane to rest position (START)	0:02:00
TOTAL	11:24:45

Table 5.6 Maintenance time for Target Assembly refurbishment

TARGET REMOVAL	
Operation	**Estimated Time (h:min:s)**
Overhead crane in rest position (START)	00:00:00
Dock the 7 DoF RBT	00:06:15
Take the ABT	00:04:00
Move the Overhead crane above the TC	00:02:00
Deploy the RBT inside the TC	00:09:00
Release the FDS in the inlet side	00:19:30
Release the FDS in the beam side (hands on)	00:15:00
Compact the bellow in the beam side	01:34:30
Release the FDS in the outlet side	00:31:00
Extraction of the RBT from the TC	00:02:00
Back the overhead crane to RBT docking station	00:02:00
Release the ABT	00:04:15
Release the RBT	00:06:15
Dock the TA gripper	00:06:15
Move the Overhead crane above TC	00:02:00
Deploy and align the TA gripper in the TC	00:23:15

Dock the TA	00:04:00
Lift the TA	00:23:45
Extract the TA from the TC	00:13:45
Transfer the old TA to the hot cell (not included in the simulation)	00:04:00
Release the TA on its support	00:20:00
Back the overhead crane from hot cell(not included in the simulation)	00:04:00
Release the TA gripper on its support;	00:10:00
FLANGES CLEANING	
Dock the 7 DoF RBT	00:05:00
Take the CT	00:04:00
Move the overhead crane above the TC	00:02:00
Deployment of the CT inside TC	00:05:00
Clean the outlet FDS fixed flange	01:20:00
Clean the inlet FDS fixed flange	01:20:00
Clean the beam FDS fixed flange	00:30:00
Extract the RBT from the TC	00:02:00
Back the overhead crane to the RBT docking station	00:02:00
Release of the CT	00:02:00
Release of the RBT	00:05’:00
TARGET INSTALLATION	
Dock the TA gripper	00:09:45
Move the overhead crane to hot cell	00:04:00
Grasp the new TA	
Back overhead crane from the hot cell(not included in the simulation)	4
Deploy and align the TA gripper in the TC	00:23:15
Position of the TA onto the supporting Structure	10:06:15
Release the TA gripper	00:02:00
Extract the gripper of the TA from the TC	00:04:15
Back the overhead crane from the TC	00:02:00
Release the TA gripper on its support;	00:10:45
Dock the 7 DoF RBT	00:05:30
Take the ABT	00:04:00
Move the overhead crane above TC	00:02:30

Deploy the RBT inside the TC	00:09:45
Close the FDS in the outlet side	00:32:00
Expand the beam bellow	01:26:15
Close the FDS in the beam side (hands on)	00:15:00
Close the FDS in the inlet side	00:27:00
Extract the RBT from TC	00:04:00
Back the overhead crane to RBT docking station	00:02:00
Release the ABT	00:02:45
Release the RBT	00:05:30
Back the Overhead crane to rest position (START)	00:02:00
TOTAL TIME	23:38:45

5.4 Conclusions

The present work shows that even complex maintenance activities can be simulated using VR engineering tools. Digital simulations indeed allowed estimating time needed for each maintenance task. Moreover the VR tools can improve the performance of the validation design process.

Currently the validation phase on the real prototype is in progress, in particular the DRP is mounted and the validation of maintenance operations is started (Figure 5.25).

Figure 5.25 Real model VS Virtual Model of IFMIF test platform (*Courtesy of ENEA Brasimone Research Centre*)

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Chapter 6 *Industrial application: Detailed design of Dorsal Fairing Bombardier C-198 assembly tool and development of assembly procedures;*

6.1 Introduction

This chapter describes an industrial application developed in collaboration with Laer Aeronautical Manufacturing. The airframe assembly processes are characterized by huge impact of human factors. In other words, in this industry field, the human are the driver of the production processes. Taking into account this aspect, the study of the interaction both between the human – product and between the human – assembly process assumes a huge impact on the reduction of direct costs of the product and on the production management. The main idea of our activities consisted in testing a new approach to the product development. In detail in every steps of the product development process the VR engineering tools help the companies to use three-dimensional master solid models and a variety of advanced simulation and modeling tools. The result is a disciplined process that eliminates non-value-added activity and provides all Integrated Product and Process Team members with the tools needed to effectively perform assigned tasks.

Relative to similar production development projects, McDonnell Douglas achieved a 40% reduction in the product development cycle time and expended 50% fewer labor hours. The higher quality build-to-package is expected to eliminate at least 80% of the engineering and tooling rework. The electronic build plan will accelerate operator learning and improve quality [11].

The activity started from a specific request by industry. Their main need was a platform to reduce time spent by workers in reading and understanding technical documentation during prototypal activities. This aspect can also contribute to improve the work flexibility, reduce the lead time of the assembly process and the probability of errors during prototypal phase.

Radharamanan asserts [2], certain areas hold the most promise for practical uses of VR: training, hazardous operations, medicine and health care, design, manufacturing, and marketing. Our work, according to the Radharamanan assumption, consists in applying of VR engineering tools to detailed design of assembly jigs and simulation of assembly process. In particular next paragraphs will describe the detailed design of C198 Dorsal Faring Jig and the development of its assembly process using VR engineering tools.

Our work describes a design environment that has been constructed to evaluate the use of virtual reality (VR) technologies for manufacturing facility design. It is observed that for manufacturing environments where the third dimension is critical to system performance, interactive three-dimensional display systems are better able to convey the information needed by facility designers. We describe several user environment design choices that seem to be appropriate for this type of application. The development of this system has indicated several areas of technological advance that are necessary before the use of VR for facility design becomes widespread [5].

These activities will introduce the application of digital methods to asset management by demonstrating how the process of learning can benefit from a digital approach, how product and process design can be integrated within a virtual framework and finally how the approach can be applied in a service context.

Process simulation methods, or digital manufacturing techniques, provide a set of tools and resources which simultaneously equip the design engineer with a means of exploring design choices, retaining a record of changes, and outputting instructional materials for the purpose of directing manufacturing staff or training maintenance staff during the product's operational life. The major advantage of process simulation is the ability to investigate design solutions at an early stage of product development previous to any commitment to physical assets. In essence, these digital models provide a means of testing incremental changes to gain rapid feedback on the consequences in order to make continuous adjustments and adaptations, so called "*Single loop learning*" [7].

6.2 Overview on the Dorsal Faring Assembly

The C198 dorsal fairing Figure 6.1 is a typical aeronautical assembly with aluminum components. The main components of the assembly are aluminum ribs and skins.

The sub-assembly is designed using the "part-to-part" assembly process. "*Part-to-part*" assembly is an assembly process where any interface management is conducted preassembly allowing a rapid one-way assembly process. Part-to-part assembly may therefore be seen as the key requirement for an efficient build process. A full *part-to-part* assembly process would involve either interchangeable components or predictive fettling, shimming and holes placement being carried out prior to assembly. Currently part-to-part assembly is commonly achieved through interchangeability but achieving this using predictive processes is relatively unknown [1].

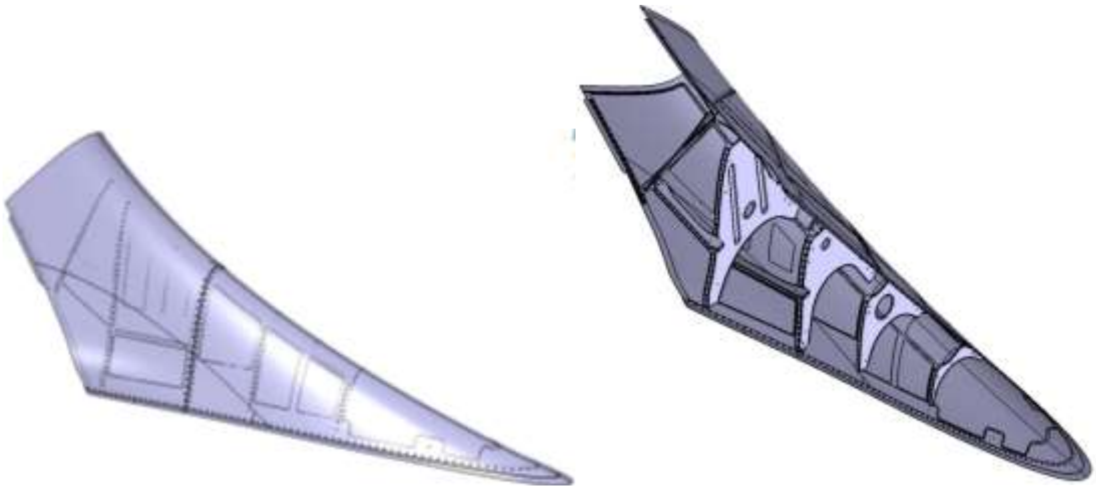

Figure 6.1 3d model of dorsal fairing

6.3 Design of Dorsal Fairing assembly Jig and VR engineering tools

The activity concerned detailed design of C-198 Dorsal Fairing Jig, took into account also the ergonomic requirements of the tools. In particular, the Dorsal Fairing assembly is made by human workers that interact with jigs, for this reason ergonomic aspects have a relevant role in tooling design. During the jig design phases, accessibility and visibility analyses have been conducted using Jack by digital human model Siemens Figure 6.2.

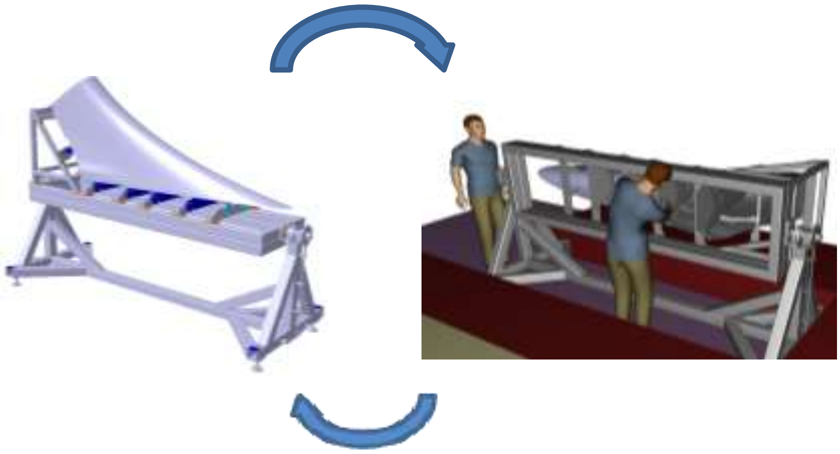

Figure 6.2 Accessibility and visibility analyses during the dorsal fairing jig design

It should be noted that the analyses were conducted in parallel with the detailed design phase. This aspect guaranteed the possibility to make changes easily during the design phase and without impacts on the jig production phase. This methodology was appreciated by the designers because supports them in evaluating of the interaction between the operators, the jig and the ancillary tools (such as drill, riveting machines, and screwdriver) (see Figure 6.3).

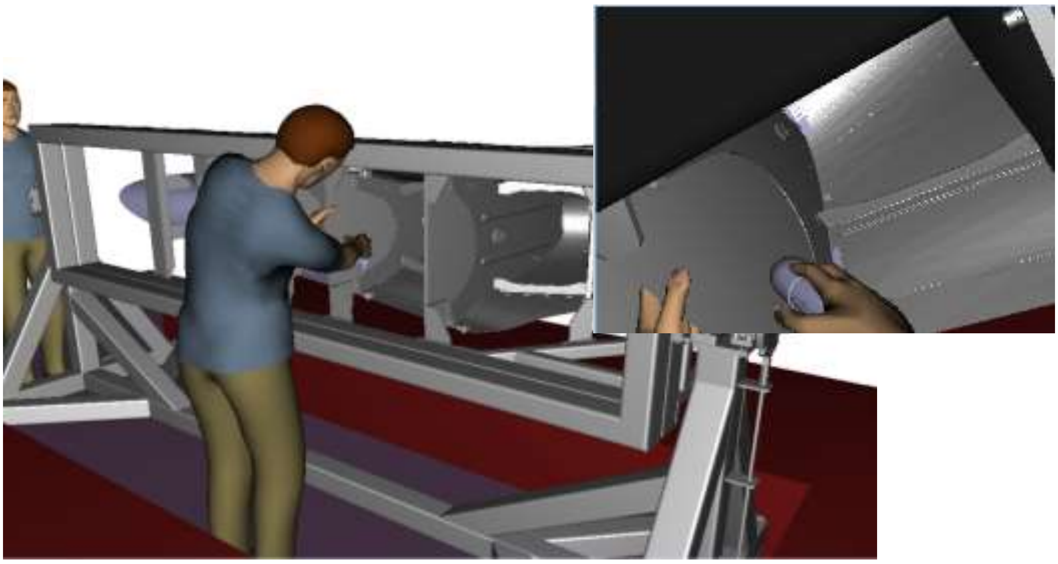

Figure 6.3 Accessibility and visibility analysis

During the design phase also ergonomic analyses have been performed according to EDIVE Methodology [12], the main objective of the analyses consisted in checking if the jig design could guarantee that all human working postures could be correct from the ergonomic point of view (see Figure 6.4). This aspect in the last years assumed a relevant importance from industrial safety point of view. Also in the Italian law regarding the industrial tools (d.lgs 42/2006) [13] are reported prescriptions from ergonomic point of view. The analyses previous described are performed for each human postures, in order to validate the jig design and to analyse the dorsal fairing assembly process.

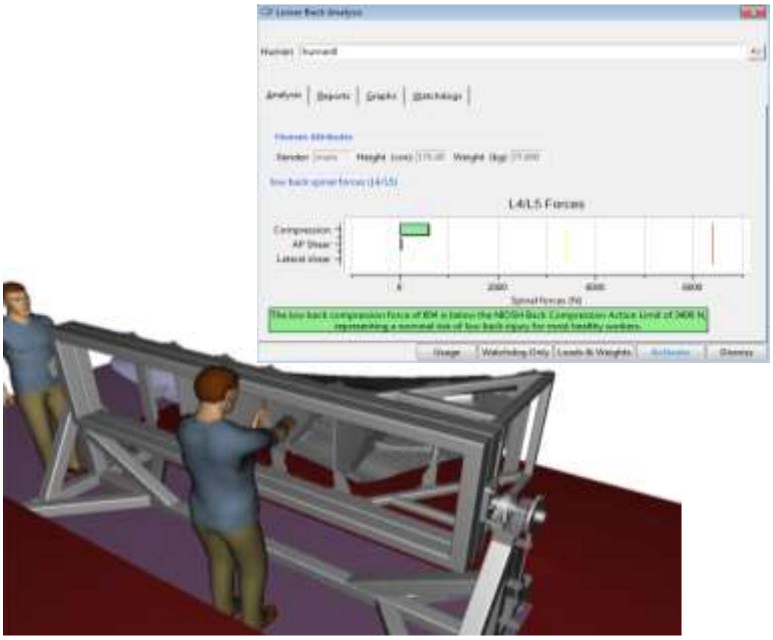

Figure 6.4 Low back analysis [12]

At the current stage the design of tool is ready, the jig was built. The company is assembling the Dorsal Fairing. In Figure 6.5 are illustrated both the virtual and real model of the assembly jig.

Figure 6.5 Physical model VS digital model of the dorsal fairing jig (Courtesy of LAER Aeronautical Manufacturing)

6.4 Simulation and development of Dorsal Fairing Assembly procedures

An assembly Work Instruction describes an assembly task to be executed by a worker. Basically, it describes the sequence of operations to carry out and their corresponding parameters: illustrations of the components to assembly, the tooling and jigs to use, the tighten torque to apply, the characteristics of sealants and their application, tolerances and applicable standards. Traditionally, all the assembly tasks had a paper based text document and a 2d-drawing of the assembly (see Figure 6.6 and Figure 6.7).

LAER S.r.l. — **CICLO DI MONTAGGIO**

*** SEZIONE OPERAZIONI ***

OPER N°	REPARTO		DESCRIZIONE OPERAZIONE	VISTO PREDIS.	DATA	VISTO COLL.	DATA	VISTO CLIENTE
5	GM	D	PRELEVARE I PARTICOLARI ELENCATI NEL KIT DI MONTAGGIO DA ASSEMBLARE					
10	CQ	D	IDENTIFICARE I PARTICOLARI DEL KIT DI MONTAGGIO					
15	MA	D	[illegible]					
20	CQ	D	CONTROLLO POSIZIONAMENTO PARTI SEC. PDC N° [illegible]					
25	MA	D	[illegible]					
30	CQ	D	CONTROLLO POSIZIONAMENTO PARTI SEC. PDC N° [illegible]					
35	MA	D	[illegible]					
40	CQ	D	CONTROLLO POSIZIONAMENTO PARTI SEC. PDC N° [illegible]					
45	MA	D	[illegible]					
50	CQ	D	CONTROLLO POSIZIONAMENTO PARTI SEC. PDC N° [illegible]					
55	MA	D	[illegible]					

Figure 6.6 List of assembly task (Courtesy of LAER Aeronautical Manufacturing)

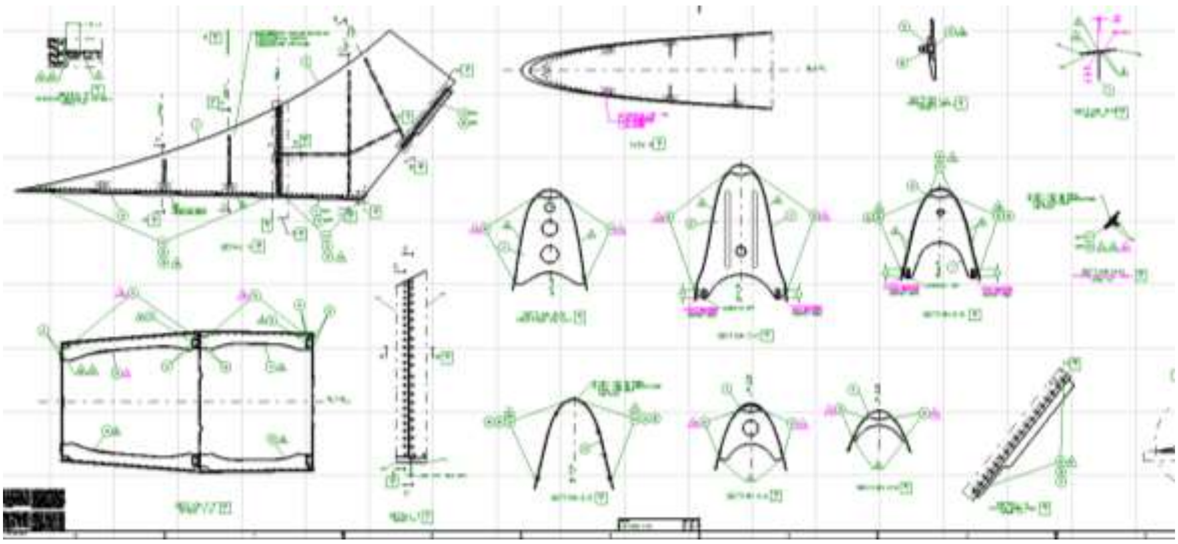

Figure 6.7 Assembly drawing

However, a great variety of assembly tasks exist and a paper based text document is not the best alternative for all of them. Different types of assembly tasks require the information to be presented in different formats and support means. Many assembly tasks deal with the repetition, a high number of times, of one or a reduced number of basic actions, which have short time duration [3].

At the heart of the animated work instruction research presented here, is the drive to facilitate user responses to complex engineering activities in a more realistic, temporal, and dynamic way. Virtual representation of three dimensional components and their motions, with respect to a manufacturing assembly sequence or a maintenance operation, has the obvious advantage over traditional two dimensional formats in that there is no requirement for additional prompts or directives over and above the provision of a drawing, static image or diagram. For example, in two dimensional instructions the fitting of one component with another may require several symbols such as arrows or direct textual instructions to convey the meaning, as well as a formerly developed knowledge base of all tooling to be used, how fasteners are used, and how to operate fixtures. This in essence requires further interpretation on the part of the operator before carrying out the task. Virtual, or immersive, instructions require only that the operator observes the action and repeats what he/she sees. From the perspective of the manufacturing sector, the objectives for improved learning capacity include shorter learning curves and reduced error rates leading in turn, to significant cost reductions and delivery lead times. Tang [8]reports an 82% reduction in error rate, NASA [9]report an 83% reduction in error rate and 24% reduction in time to completion, and Lin [10] reports an approximately 45% reduction in time to completion when virtual training methods are employed.

After the design of the Dorsal Faring jigs, its assembly process was defined, together with the industrial engineering personnel, and then simulated using VR engineering tools. The outcomes of this phase consist in validation of the jig project from the assembly cycle point of view and in definition of the optimal assembly procedure. It should be noted that all the described phases are strongly linked and as we can imagine the VR Engineering tools supporting the industrial context in the management of the product development process. At the end of the procedure development process the outputs of this phase were summarized in a digital movie that represents in detail the overall assembly process. This movie is currently used as internal document of the company. The video is very useful to show all information from accessibility and visibility analysis, ergonomic analysis and working time analysis. Also the layout of the assembly area of the Dorsal Faring was designed Figure 6.8.

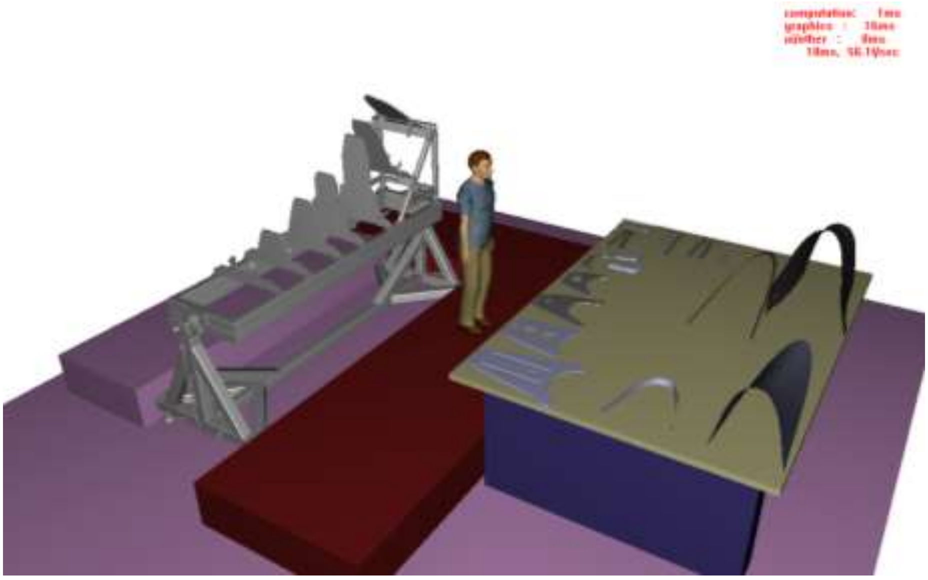

Figure 6.8 Layout of the assembly area of Dorsal Fairing

Simulations were used to develop and validate specific procedural options using animations with clash detection functions, as well as ergonomic analysis. In essence, the digital tools used here, allow the designer to test engineering decisions using criteria fundamental to part assembly and replacement, and thus generate an optimal solution to identify and quantify, the costs associated with this type of assembly activity. From a learning perspective, the ability of the design engineer to attempt design features which may not have been familiar to them previously, to test those concepts and accept or reject those proposals dependent on the result, and to collaborate with industrial engineering experts through a universal visual medium, is a powerful tool in the arsenal of learning.

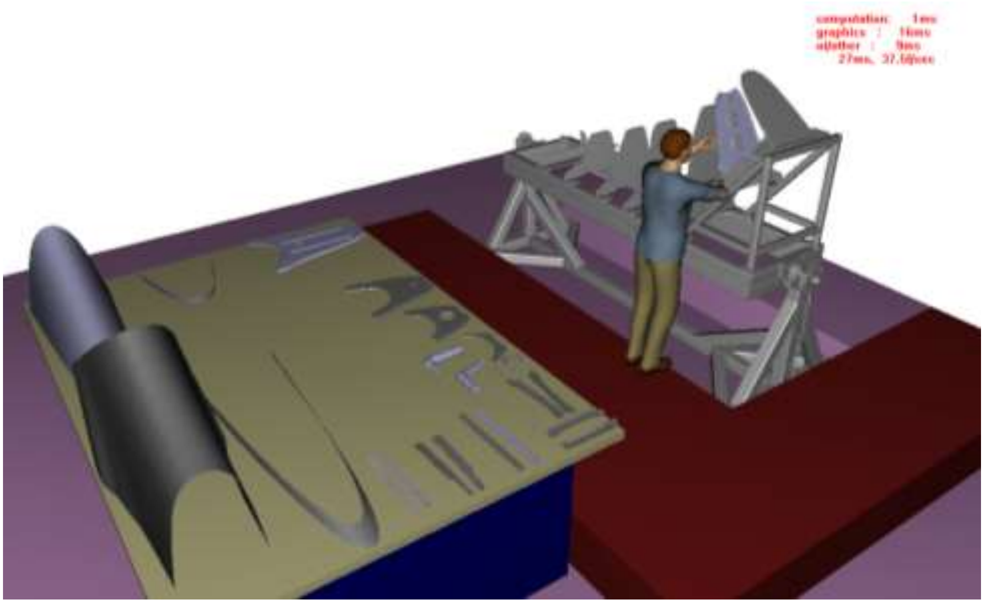

Figure 6.9 Single step of the assembly process

The Figure 6.9 represents a single frame from a fully animated process definition which included detailed representations of each task required to complete the work.

6.5 Conclusion

The concept of applying digital methods directly to learning in the airframe assembly process has been demonstrated in the case of Dorsal Fairing. Our research demonstrated that VR engineering tools potentially may give better support to the production process than a paper guide. Moreover the VR engineering tools used in detailed design process give a precious support to the design teams. Using this methodology the design could be validated taking into account not only technical requirement but also ergonomic and safety requirement. This project demonstrated that three-dimensional master modeling can eliminate two-dimensional drawings and enable physical mockups to be replaced by computer-generated virtual prototypes. The project also demonstrates use of several advanced simulation tools for the product design, the assembly tooling, and the manufacturing processes. Future works will consist in quantitative analyses in order to estimate the benefits due to use of VR engineering tools in industrial contexts.

6.6 References

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Chapter 7 *Industrial application: Web Based Multimedia Manual of Local Train*

7.1 INTRODUCTION

In the present chapter will be described the methodology supporting the product maintenance management. The VR tools contributed to the project validation from maintenance point of view taking into account also the aspects related to the human – product interaction.

In particular in order to face the problems due to interaction human-product, our research group has been working since years on developing a design review methodology (*Virtual Design Review*) based on the synergy between *Virtual Reality* (VR) and *Digital Human Modelling* (DHM).

VR technologies allow designers to interact in real-time with digital mock-ups inside a single Virtual Environment (VE), while DHM tools make it possible an objective and measurable analysis of the human factor in the context of use of the future product.

From this point of view, one of the first attempts has been made by Gomes and Zachmann [1]that investigated the use of VR and to simulate assembly and maintenance processes on a digital mock-up.

Nowadays, these technologies are proved to appreciably help to cut time and cost of product development. In particular, organizations using VR can reduce lead time to market by 30% and the number of design changes by 65% [3], [4].

Published literature agrees that the capabilities of DHM tools go over and above the mere graphical simulation [4], but instead they can be effectively used to conduct very detailed ergonomic analyses [5].

For instance, Chang [6] proposed a method of conducting workplace evaluations in the digital environment for the prevention of work-related musculoskeletal disorders using DELMIA of Dassault Systemes. Several authors [7], [8] have demonstrated that DHM ergonomics simulations provide good estimations of the workload in real-life tasks, correctly predicting ergonomics issues for standing and unconstrained working postures.

These analyses can be used also in the fields of maintenance.

This is a quite subtle, but important problem. For instance, referring to aeronautic industry, many authors have shown that the 45% of maintenance time is spent in reading technical documentation [9],[10]. Thus, several attempts exist in the published literature to develop new modalities for administering technical documentation. Many researchers are working on Augmented Reality (AR) systems. Schwald [11] described an AR system for training and assisting in maintaining equipment in industrial context. Azuma [12] describes the characteristics of AR systems, including a detailed discussion of the tradeoffs between optical and video blending approaches. Toro [13] presented a system implementation for the exploitation of embedded knowledge in the domain of industrial maintenance in a mobile context. As test case, it implemented an approach in different portable devices with video input capabilities such as PDAs and Tablet PCs.

On the contrary, the present paper shows how VR and DHM can be also used to draw-up multimedia maintenance manuals.

Actually, several examples of multimedia manuals exist in the published literature [14] [15]. However, generally these manuals just consist of a set of short videos that only show mounting sequences and assembly of parts. In general, the movements of workers needed to perform a certain task are not considered at all, or, at least, they are not shown.

Instead, the design approach presented in this paper assumes the human factor to be central since the very first steps of product design, according to the doctrine of *concurrent engineering* [16]. Thus, the development of maintenance procedures is a matter of course.

It is worth noticing that every good product needs, in any case, the study of its assembly and its disassembly procedures, just as accessibility, ergonomics and working-time analyses. Therefore, as a part of the product design process, technical documentation of a product can be made at virtually no cost.

7.2 Virtual Design Review and Multimedia manuals

Virtual Design Review (VDR) is a methodology that uses VR technologies to improve the development and the critical review of projects [17].

VDR allows designers to see and manipulate virtual products in real-time, evaluate several design solutions, simulate assembly and maintenance tasks, take measures, verify visibility, etc.

Furthermore, by means of digital human models, VDR make it possible also to conduct ergonomic analyses on a product or a certain task in real-time.

Historically, the main barriers to the spread of VR in industry was the cost of the equipment and the size of their operating space.

Therefore, during the last years our research group has spent some efforts in the study and development of low-cost VR solutions, ensuring high quality standards. From this point of view, our VR laboratory IDEAinVR (*Interactive Design and Ergonomics Applications in VR*), equipped with two stereoscopic frontal projection systems and advanced motion capture systems, is definitely a viable and low-cost model for the diffusion of the described technology into the industrial field, Figure 7.1.

Figure 7.1 IDEAinVR Lab

The equipment of IDEAinVR lab is described in more detail in table 1.

Table 7.1 Equipment of IDEAinVR lab for Virtual Design Review.

Name	Description	Qty
Depth-Q HDs3D	DLP 3D projector	1
Sanyo PDG DWL-2500	Ultra-short optics DLP 3D projector	1

IoTracker	IR Tracking cameras	4
DELL Precision	Workstation	2
Cyberglove	Hand gesture recognition device	1
3DConnexion	Spacemouse	2
Nintendo Wii-remote	Wireless controller	1
Microsoft Kinetic	Desktop-based motion sensing device	1

This configuration has at least 3 significant advantages over ordinary frontal projection systems:

- ✓ Thanks to the ultra-short optics, user can come close to the screen during the simulation, up to a distance of 20 cm without casting shadows.
- ✓ Those involved in the design review session can follow the analysis on a second screen, larger than the former, without visual occlusions due to the user standing in front of the first screen.
- ✓ The two screens can also be used to display different information. For instance, while the first screen is displaying the simulation, the second one can show CAD models, results of FEM/CFD analyses, etc.

This solution is cheaper than a rear projection system and can be easily installed even in small environments.

This approach has well-known benefits, if compared with traditional desktop-based design review. In particular:

- ✓ many design solutions can be evaluated in real-time,
- ✓ Complex CAD models can be loaded and handled in real-time,
- ✓ easy detection of technical problems thanks to stereoscopic visualization,
- ✓ optimization of the information flow about the project, thanks to a more collaborative environment,
- ✓ Real-time evaluation of possible ergonomics issues,
- ✓ Real-time simulation of tasks related to the process/product (e.g. maintenance operations).

However, apart from these clear benefits, VR-based analyses have some weaknesses. For instance, the backward propagation of information coming from design review is still an open issue, due to the lack of a generally accepted protocol for transfer data between PDM and VR environments and vice versa.

Indeed, feedback data are often very heterogeneous, involving entire processes and more than one CAx tool of different software vendors. This is particularly penalizing for complex projects developed on international basis.

Nevertheless, at least with reference to maintenance analyses, a possible way of propagating the results of VR simulations to maintenance operators is through so-called "multimedia manuals". In particular, this paper focuses on a structured methodology that uses VR and DHM to study the maintenance procedures for the pneumatic brake system of a metropolitan train. Then, the information coming from these analyses are used to draw up a web-based multimedia maintenance manual.

7.3 Methodological approach

The methodology that is being discussed here is essentially based on EDIVE [18] approach, that is summarized in Figure 7.2.

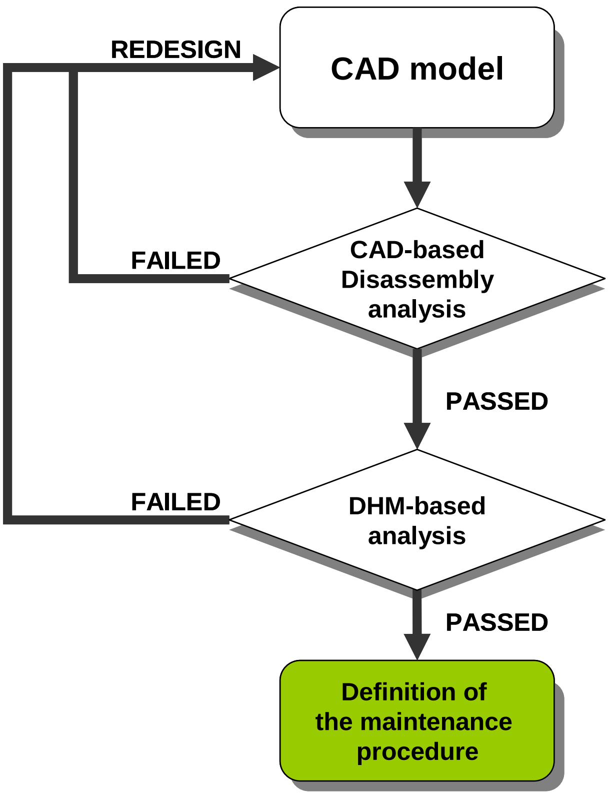

Figure 7.2 Main steps of EDIVE methodology

More precisely, in a first phase, CAD modules aimed at collision-free path planning are used to verify the detachability of assembly components [19], [20]. After that, DHM tools are used to perform more detailed analysis about the actual feasibility of the considered maintenance task.

On the one hand, EDIVE methodology can answer in a precise and an objective way to the problems related to maintainability of industrial products and it can provide objective information about ergonomics of the posture assumed by workers, considering the human comfort as the fundamental requirement to observe [25]. DHM tools also allows estimating maintenance time as function of a desired “comfort level” for critical tasks. Therefore, the maintenance sequences can be defined considering the trade-off between the comfort perceived by maintenance staff and time/cost requirements. In this way, several assembly and disassembly procedures can be digitally evaluated until the final maintenance procedure is defined [25].

Unfortunately, on the other hand, such methodology can be quite hard to implement, mostly because of the time needed for the “animation” of the human figures.

In fact, despite different software solutions have been developed fit for purpose, quick simulation of human behavior in constrained environments is still a challenge, at least with reference to complex scenarios. In these cases, very specialized skills are needed, similar to those required to cartoons animators of entertainment industry [26]. A proper set of "key posture", needed to achieve the desired task, have indeed to be defined for the digital human, taking account of many physical constraints, such as the presence of obstacles along the disassembly path. It is understood that the simulation of complex scenarios can be very time consuming and can represent a significant cost for the industry and a barrier to the use of such simulation tools.

Therefore, when maintainability analyses involve complex assemblies (that means simulating hundreds of tasks) EDIVE methodology becomes definitely unsuitable.

However, it must be noticed that, even for complex assemblies, generally just a small subset of maintenance operations really deserves the use of specific DHM tools.

VR technologies are, indeed, known to be an effective way of simulating human movements in real-time, thanks to motion capture systems and VR devices (e.g. “virtual gloves”) that allow users to naturally interact with virtual objects inside a computer-generated environment (see Figure 7.3).

This kind of real-time interaction can be used to simulate maintenance tasks very quickly (VR-based analysis). For instance, a digital mock-up can be entirely disassembled by means of “virtual tools”.

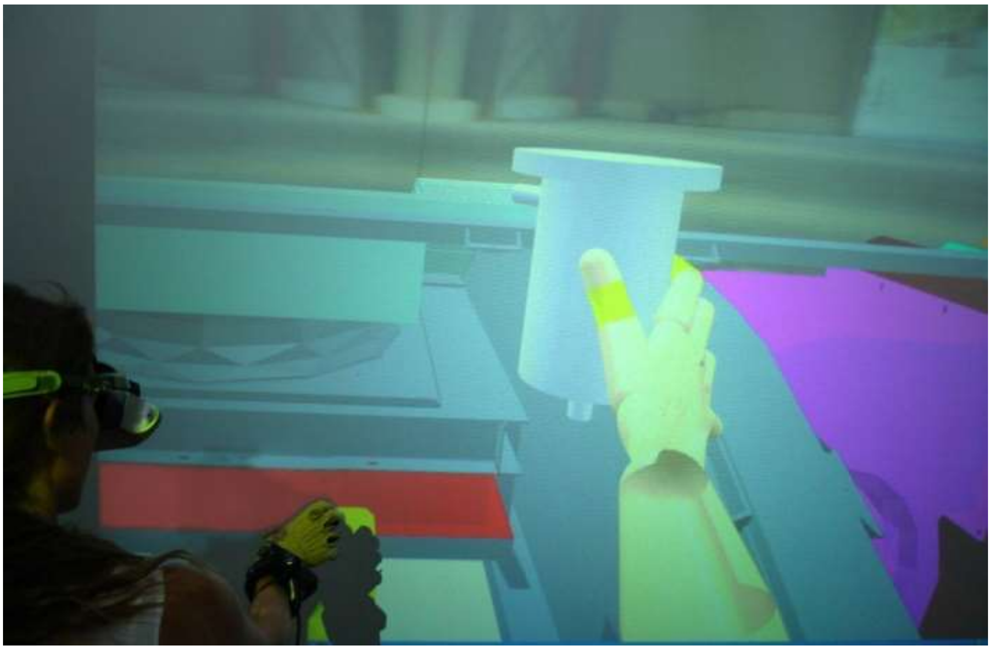

Figure 7.3 VR-based maintenance simulation

Therefore, the workflow of EDIVE can be modified as shown in Figure 7.4.

DHM tools will be used only when VR-based analysis is not applicable because the human-product interaction is very complicated (e.g. complex kinematic mechanisms) or when the results of VR simulation are uncertain from an anthropometric point of view.

In other words, VR technologies act as sort of “filter” on the great number of possible maintenance operations. Then, DHM tools can be used to conduct more detailed ergonomics analyses only on a limited subset of maintenance operations (critical maintenance tasks).

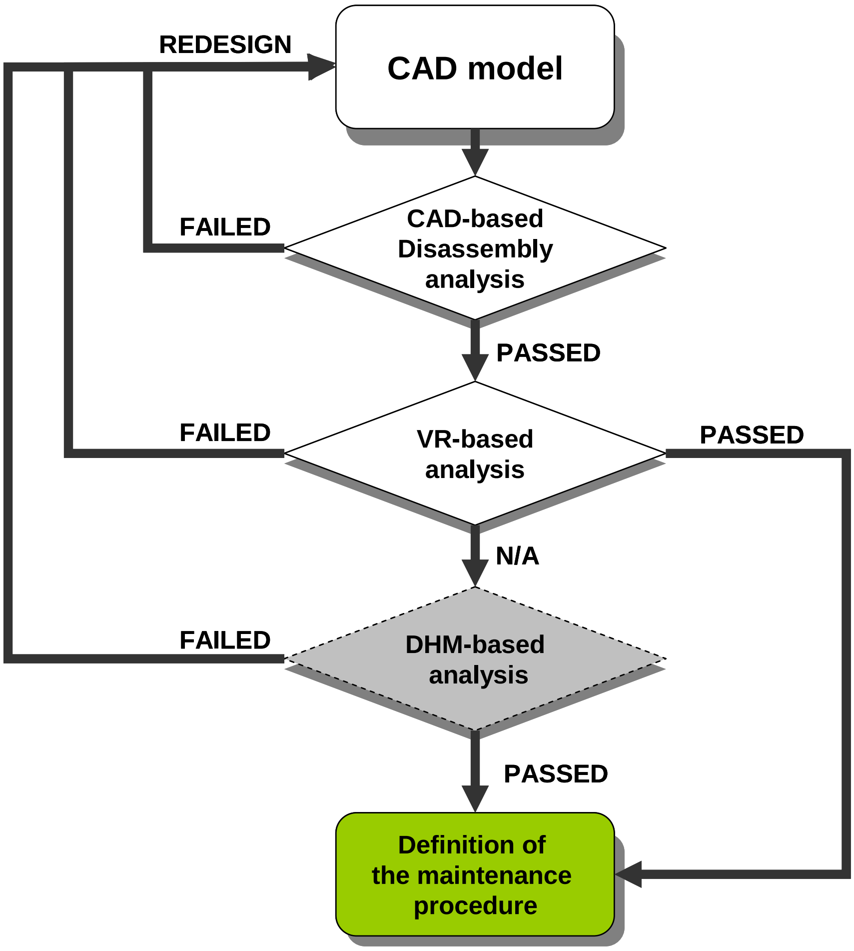

Figure 7.4 Methodology of maintainability analysis of complex assemblies in virtual environment.

It must be noticed that both VR-based and DHM-based analyses have a useful "side-effect": video animations can be recorded during the simulations and then properly edited with subtitles. Moreover, collaborative environments like our IDEAinVR lab help maintenance engineers to get involved in maintenance simulation.

In this way, digital animators can solve many issues related to production and maintenance operations. Thus the synergy between VR software and DHM tools can be used to identify design errors that affect the maintainability of the product and to propose design solutions that better take into account the human factor.

In this way, possible design errors can be highlighted before physical prototypes are built. This is particularly important because, at this stage, the proper design changes can be done at very reduced costs.

Finally, all this information can be collected to become the bases of a *multimedia maintenance manual*.

7.4 Web-based maintenance manuals

The use of multimedia applications for information transmission is becoming a quite common practice in industry. In particular, several authors have studied new modalities to train and to drive workers in maintenance operations.

Multimedia maintenance manuals potentially may give better support to the maintenance engineer than a paper guide. However, a “static” multimedia manual could not significantly reduce learning time and therefore maintenance cost [27] because maintainers, nevertheless, has to read the instructions, understand them, remember them and apply them correctly [28]. Moreover, all these processes are prone to errors, especially omissions [28].

In order to face this kind of issues the authors have developed a web-based maintenance manual based on the information coming from VR and DHM analyses (see Figure 7.5).

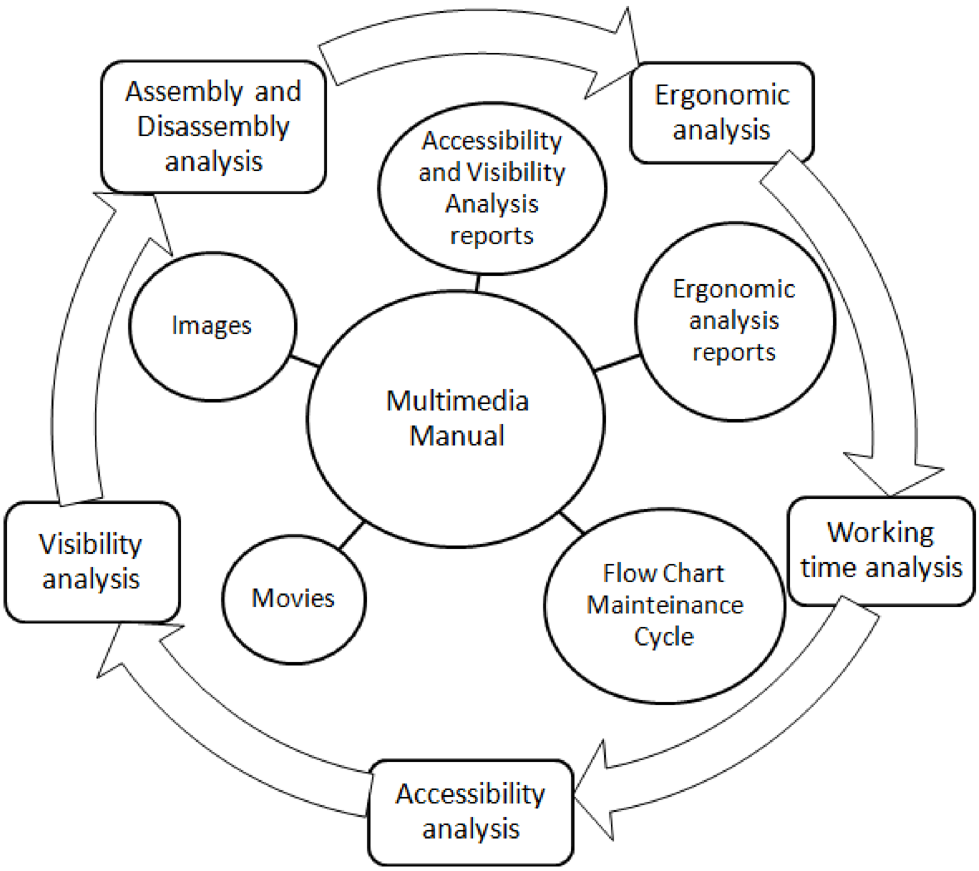

Figure 7.5 Multimedia manual information flow

One of the main goal of the methodology is to shorten the consultation and learning time of maintenance operations. Apart of the direct benefits in terms of maintenance costs, multimedia manuals can also significantly shorten maintenance downtimes and therefore reduce production costs.

Moreover, video animations help maintenance engineers to learn assembly and disassembly sequences, since the operator can pause and watch videos any time until he well understands every phase of the maintenance task [29].

All the information produced has become part of a web-based application that improves the accessibility and availability of the contents. In this way, possible flaws in documentation can be detected and fixed on-line. The changes are then propagated in real-time to maintenance engineers.

7.5 Case study

The case study has concerned the pneumatic brake system of a regional train. The main goals of the work were:

- ✓ *detecting the critical maintenance operations;*
- ✓ *defining a step by step maintenance workflow;*
- ✓ *determine maintenance time;*
- ✓ *drawing up a multimedia maintenance manual.*

The first objective has been pursued by means of VR technologies. Several designers, maintenance engineers and workers have been involved in the design review activity, making useful suggestions. In particular, the following three areas have been detected and considered critical from an ergonomic point of view:

- ✓ Head area
- ✓ Rear underbody area
- ✓ Under ceiling area
- ✓ These areas have been further studied by beans of DHM tools (Siemens Jack®).

In order to accurately simulate manual operations, also maintenance tools have been digitally reproduced. Moreover, since the train was still under development, some missing CAD models replaced with simplified geometries.

7.5.1. *Head area*

VR-based analysis highlighted that some fittings in the *head area* was not accessible at all. For this a hatch (Figure 7.6, Figure 7.7) has been added to the original design.

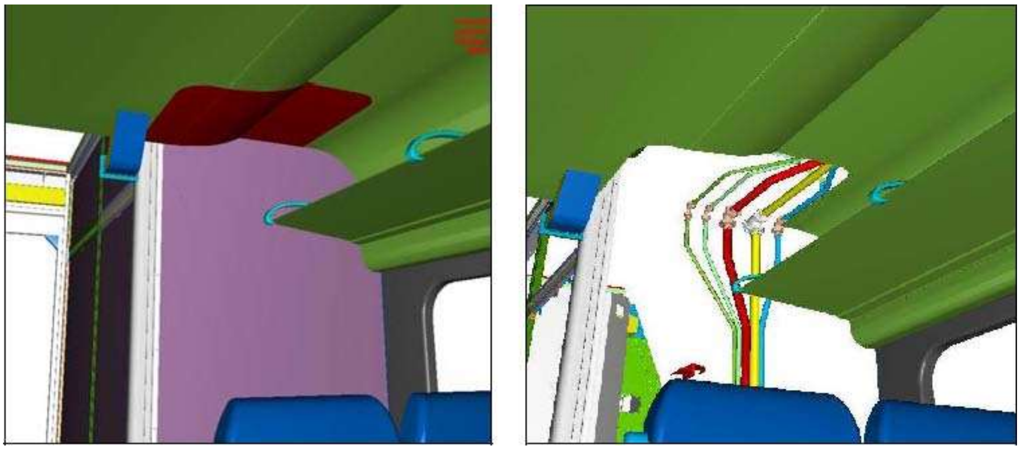

Figure 7.6 New hatch for fittings inspection

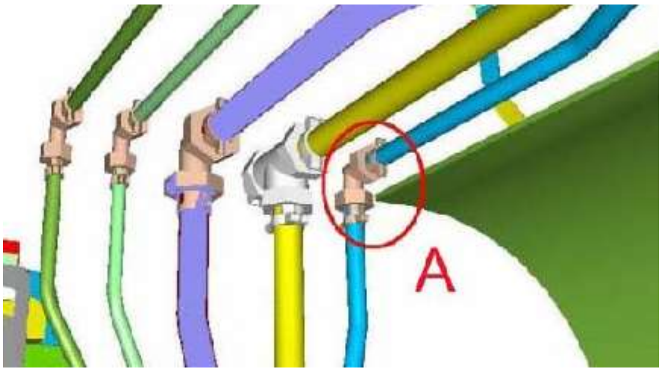

Figure 7.7 Most critical joint

7.5.2. *Underbody area*

Rear underbody area needs some preventive maintenance. VR analysis showed that most of the fittings can be inspected visually. Their accessibility has been verified with Jack® (Figure 7.8).

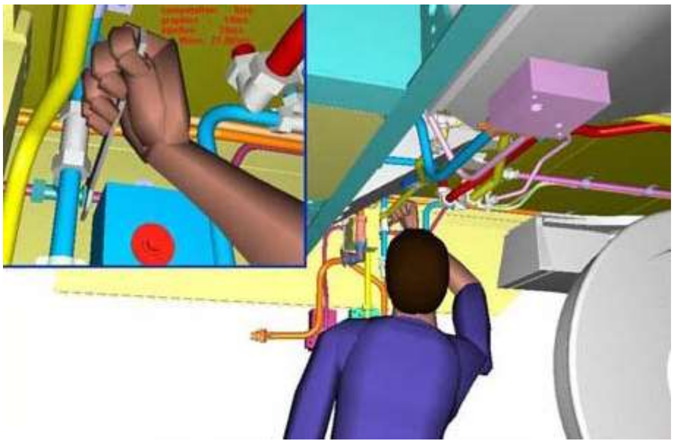

Figure 7.8 Maintenance task in underbody area

7.5.3. *Under ceiling area*

VR simulation showed that under-ceiling area needed some maintenance analyses. Jack® has been used to simulate the tightening of some connections.

The analysis has highlighted some flaw in the original design that has been consequently modified.

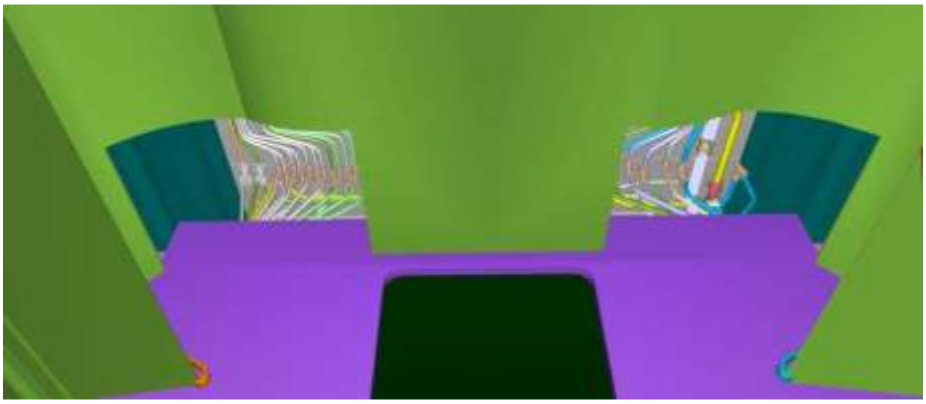

Figure 7.9 Fittings under ceiling area

Moreover, several maintenance sequences have been compared based on the comfort perceived by the operator (Figure 7.9, Figure 7.10).

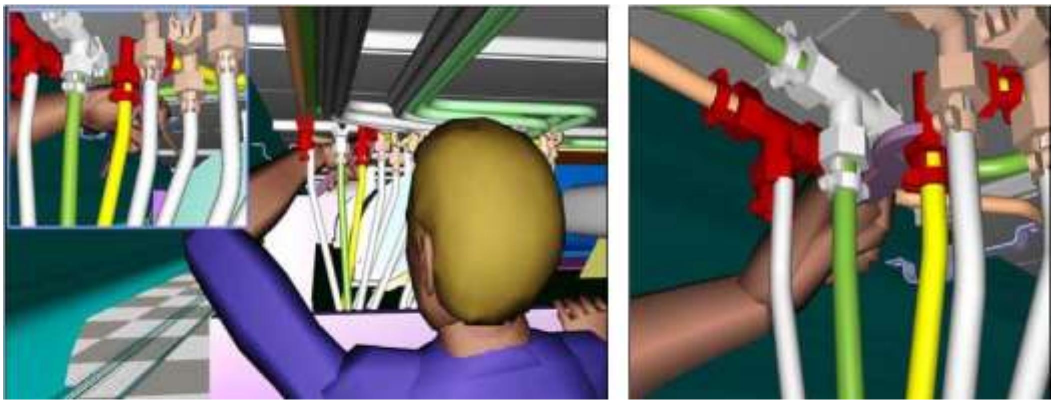

Figure 7.10 Checking of under ceiling fittings

7.6 Multimedia manual

The information coming from the previous analyses has become the matter for the digital manual. The data has been arranged in a tree structure. A certain number of thematic areas are on the top of hierarchy that the user can select by clicking on its thumbnail (or even touching on it, if a touch-screen is used). Each area has certain components to be maintained. Each component has further sub-components and each of these has several maintenance operation associated with.

Finally, once user select a maintenance task, a digital video animation is displayed along with a detailed report on every phase of the selected maintenance operation.

Figure 7.11 shows the resulting digital maintenance manual developed for the case study.

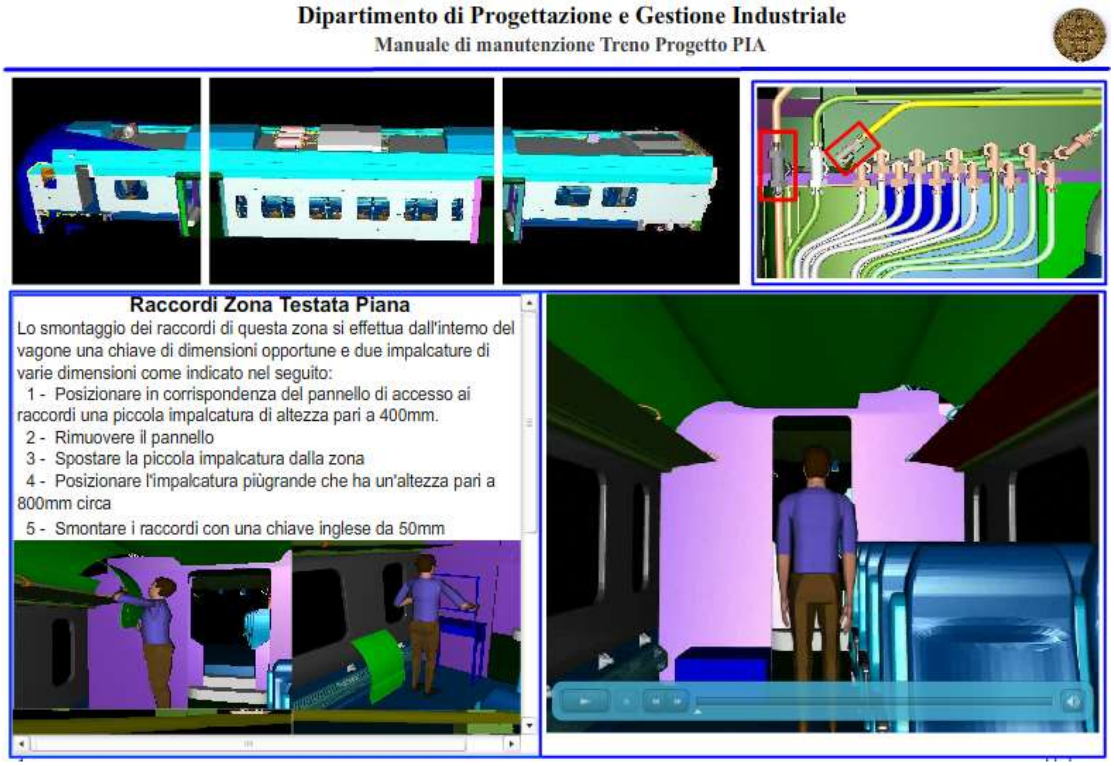

Figure 7.11 Multimedia manual screenshot

As aforementioned, the multimedia manual contains all the information coming from previous stages of product design.

In particular, the digital manual includes:

- ✓ short videos that show assembly and disassembly operations and the correct human movements;
- ✓ flow charts of the entire assembly cycle;
- ✓ images showing human working postures in detail;
- ✓ accessibility and visibility analyses reports;
- ✓ ergonomic analyses reports;

The videos are very useful to show all information from accessibility and visibility analysis, ergonomic analysis and working time analysis.
Accessibility and visibility analysis define the components disassembly paths taking into account limbs operator dimension.
Ergonomic analyses define the “correct” working postures that are a trade-off between ergonomics and working-time requirements.
Man-hours needed for each task are evaluated through MTM method.

The flow chart of the maintenance cycle describes the workflow and the tools needed for each operation. It specifies as well the quality checks to perform after each task.
Accessibility and visibility analyses reports show disassembly paths and highlight the critical tasks (characterized by limitations both in working space and visibility).
Finally, ergonomic analyses reports justify the postures chosen for maintenance workers.

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Chapter 8 *CONCLUSION*

The present research focused on development of a methodology to implement the VR engineering tools in all phases of the product lifecycle. The possibility to test the methodology on real contexts and on real product was fundamental to test our theoretical approach in industry field. Due to this it was possible to get a feedback in order to improve the method structure.

The research has shown how VR engineering tools can support a system lifecycle approach to manufacturing process development and its management. The method used here shows how these technologies can deliver tangible outcomes in terms of shared objectives in the design teams. Future works will involve quantitative analyses to estimate the benefits arising from their use in industrial contexts.