Concept design of the DEMO divertor cassette-to-vacuum vessel locking system adopting a systems engineering approach

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HIGHLIGHTS

- An iterative and incremental design process for cassette-to-VV locking system of DEMO divertor is presented.
- Three different concepts have been developed with a systematic design approach.
- The final concept has been selected with Fuzzy-Analytic Hierarchy Process in virtual reality.

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ABSTRACT

This paper deals with pre-concept studies of DEMO divertor cassette-to-vacuum vessel locking system under the work program WP13-DAS-07-T06: Divertor Remote Maintenance System pre-concept study. An iterative design process, consistent with Systems Engineering guidelines and named Iterative and Participative Axiomatic Design Process (IPADeP), is used in this paper to propose new innovative solutions for divertor locking system, which can overcome the difficulties in applying the ITER principles to DEMO. The solutions conceived have been analysed from the structural point of view using the software Ansys and, eventually, evaluated using the methodology known as Fuzzy-Analytic Hierarchy Process. Due to the lack and the uncertainty of the requirements in this early conceptual design stage, the aim is to cover a first iteration of an iterative and incremental process to propose an innovative design concept to be developed in more details as the information will be completed.

1. Introduction

One of the challenges in the roadmap to the realisation of fusion energy is providing DEMO with more efficient solution for remote maintenance. Minimising the plant down-time requires to optimise the design of the in-vessel components and their interfaces for remote handling (RH) operations from the outset [1].

As regards divertor replacement procedure, one of the most important aspects that affects the maintenance time is the cassette-reactor connection. The main functions of the DEMO divertor cassette-to-vacuum vessel locking system is to provide a remote-handling-compatible means of locking and unlocking of the cassette [2]. The system aims to provide reliable fixation of the DEMO divertor cassette in the vacuum vessel (VV), under different thermal and electromagnetic loads, during the operational mode of the reactor.

This work deals with the conceptual design stage of divertor cassette-to-vacuum vessel locking system, under the work program WP13-DAS-07-T06, proposing a design methodology to address the requirements management and the early stage of the design.

The system engineering approach in the definition of the requirements has been followed in the beginning of the system development. In complex situations with a number of parties involved, such as this early stage of DEMO project, the design process starts when the requirements are not completely defined from the beginning and some of them can be fully known only during the design process. In order to overcome these difficulties, this paper proposes a design process for drafting solutions in an "incomplete requirements environment". In this kind of approach, the information will be completed during the design phase, as this situation may occur in complex projects during early conceptual design stages.

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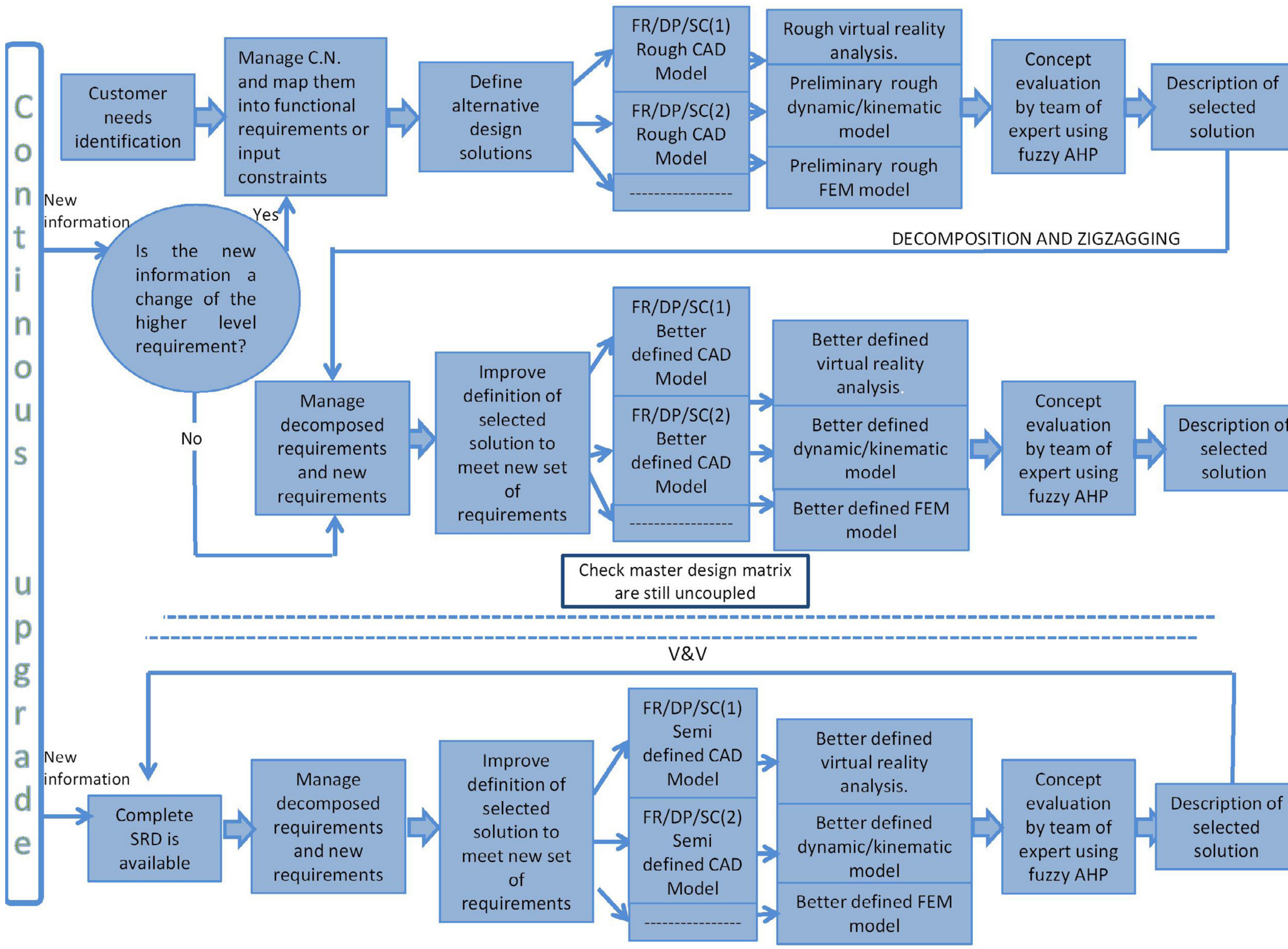

Fig. 1. Iterative and Participative Axiomatic Design Process (IPADeP).

The process suggested in the generation of the locking system concepts is named Iterative and Participative Axiomatic Design Process (IPADeD). It is an iterative and incremental design process, participative and requirements driven, based on the theory of Axiomatic Product Development Lifecycle (APDL) [3,4]. IPADeP provides a systematic methodology in which starting from a set of experts assumptions, a number of concepts are generated and evaluated (Fig. 1). According with the axiomatic design theory [5], the first iteration of the process starts from the Customer Needs identification and the definition of few Initial Functional Requirements (FRi). Then alternative design solutions to meet these requirements are defined, in terms of Design Parameters (DP) and system components (SC). The concepts are then analysed (FEM, kinematic analysis) and evaluated by a team of experts with the use of Fuzzy-Analytic Hierarchy Process [6,7]. Based on the results obtained, a new iteration is performed for each level of decomposition and as the requirements are completed. Following this process and assuming as starting point the studies on ITER divertor locking system [8], conceptual solutions for DEMO divertor cassette-to vacuum vessel locking system are conceived and evaluated in this paper.

2. Customer needs identification

A principal objective of the task mentioned is to "explore the proposed in-vessel component attachment methods from a RH compatibility perspective, particularly with consideration of the in-vessel radiation dose level" and to "carry out preliminary design and R&D work on the problems of connections of in-vessel components following findings and recommendations of previous studies of ITER".

Pursuing this goal, meetings and discussions were carried out with experts and stakeholders to understand the different needs that DEMO divertor locking system shall meet compared to the ITER locking system. Due to the early nature of this conceptual stage the aim of these meetings wasn't the redaction of an official System Requirements Document (SRD) but the elicitation of a first set of requirements and experts' assumptions essentially based on the extrapolation of the studies on ITER RH process to DEMO.

2.1. General requirements

The development of remote maintenance concepts for DEMO fusion power plants is driven by the following key requirements and constraints:

- Maximized overall plant availability and, therefore, minimization of plant down time for the foreseen maintenance operations;
- Feasibility and reliability of the plant maintenance system;
- Harsh in-vessel environmental conditions such as radiation, activation and decay heating;

Optimized integration of tokamak systems.

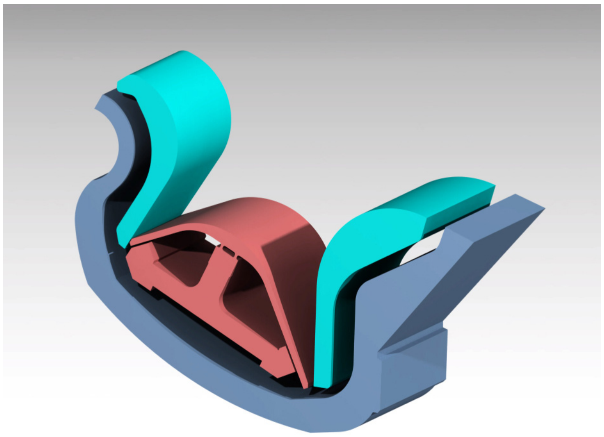

Fig. 2. EFDA original CAD model of a single divertor cassette in DEMO.

Due to the level of uncertainty surrounding the use of in-vessel materials in a DEMO relevant environment, the ability to replace and update in-vessel components within a reasonable timescale is paramount.

General requirements for the RH systems include to:

- Deliver high availability;
- Be flexible to new or changed task requirements;
- Deliver high quality operations;
- Perform operations safely.

One of the inputs of the project is the initial CAD model of Tokamak core and ancillary system generated by CCFE in CATIA software, and it will be used to build a configuration model or digital mock-up. The same model is used as starting point of design and analysis. The shape of the divertor (Fig. 2) is assumed to be fixed in the inner side, while the cassette compression mechanism con be fitted in the outer part of the cassette body due to the existing available space.

2.2. Structural and mechanical requirements

As regard the structural and mechanical requirements, dynamic structural feasibility of the divertor structural supports shall be verified based on the loads specified for the ITER divertor supports (in the ITER in-vessel Load Specification [9,10]) extrapolated to DEMO (Table 1). Following the strategy applied for nuclear installations, events and loading conditions are classified into four categories related with the expected frequency of occurrence. Categories I and II are associated to normal operational and likely events (incidents), while categories III and IV are associated with unlikely and extremely unlikely events (accidents). Acceptable damage limits (allowable values) for each condition combination are defined also based on whether the component has any safety importance or for investment protection [11]. Alongside the normal operation (NOP) condition, the load cases are analysed according to various events during the operation of the reactor, among which the Vertical Displacement Event (VDE) dominates the largest influence of all. A VDE is caused by unanticipated loss of magnet confinement inside of the vacuum vessel. These events are characterized by a sudden loss of energy followed by a large fraction of plasma current being transferred to the surrounding in-vessel components, thus generating large forces (as much as 3000 t in JET) in a very short period of time.

2.3. Materials requirements

As regard materials requirements, the effects of irradiation on metal parts only become apparent after long periods of time. Similar metals to those used in the reactor can be used for RH equipment. Exposure times however should be relatively short and at low levels compare with the structure of the reactor. According to the most recent study from the Italian power engineering company Ansaldo Nucleare (partner of EFDA), approved material for divertor ancillary parts are [12]:

- Links connecting multilink attachments: INCONEL 718
- Divertor to vacuum vessel locking system: BRONZAL (Ni-Al bronze).

All materials used in items of divertor RH equipment which enter areas served by the detritiation system shall be halogen-free (i.e. shall not contain compounds with fluorine, chlorine, bromine or iodine). Exceptions must be approved by the tritium system and safety section responsible officers.

2.4. Functional requirements

The divertor cassette to vacuum vessel locking system shall be able to perform the following main functions:

- Lock/unlock cassette in place
- Withstand high forces in any direction.
- Preload cassette in order to remove clearances
- Compatible with Remote Handling.

Table 1
Loads on outboard support.

Unit [kN]		Outboard support					Load cycles
Cat	Load case	F_{rad}	F_{vert}	F_{tor}	M_{rad}	M_{vert}	
I	Baking regime 1	178	84	0	0	0	500
	Baking regime 2	83	34	0	0	0	
	Testing	−47	−23	0	0	0	1
	Preload including heat deposition + dead weight (normal operation (NOP))	237	95	0	0	0	30000
II	MDI + MFD-II + NOP	−630	1014	−665	608	241	50
	SL-1 + MDI + NOL	747	506	−628	607	239	10
	VDEII slow down + NOP	641	391	173	−204	63	400
	VDEII fast down + NOP	658	519	−660	643	254	
III	SL-1 + VDEII slow down + MFD-II + NOP	−507	960	−153	−209	−67	<1
	SL-1 + VDEII fast down + MFD-II + NOP	−667	1088	−710	638	247	<1
	VDEIII slow down + NOP	557	615	−306	−523	−123	<1
	VDEIII fast down + NOP	627	713	−738	930	295	<1
IV	SL-II + MDI + NOL	703	564	−640	601	231	0

Table 2
Early assumptions.

Locking mechanism shall withstand operational radiation level
The divertor components are not planned to be re-used and refurbished like in ITER. That may affect the component design since the cassettes are used just once and do not require gentle handling
The cassette shall be electrically connected to the vacuum vessel via the inner and outer locking system
Locking System shall be compatible with remote installation and disassembly during divertor maintenance
Robotic manipulator for locking/unlocking operation ITER-like
Locking System shall be compatible with the transfer cask and RH geometries
Since it affects reactor availability, Locking System shall have short maintenance time. It means that Locking System shall provide simple, robust and time saving operations after DEMO harsh conditions
Inner locking shall be ITER-like nose-hook mechanism
Outer-locking simplification is necessary due to harsh operation conditions, which set higher requirements to the locking and rescue ability
Outer-locking mechanism is designed in such a way that it generates preloading with a simple mechanism to remove any clearances and avoid “shaking” due to sudden change of the magnetic field
The outer locking system should be able to generate preloading applying a force of 10-15 tons to provide the cassette a displacement of 5 mm
Outer-locking shall allow small rotations due to thermal expansion
The Locking System shall be designed to carry the maximum halo and eddy currents in case of VDEs
Magnetic force are not yet known but scaling the forces of ITER with the planned performance factor to DEMO give some estimate of the magnitude of the forces (scale factor = 1.4)
It is needed that the locking systems carry load in all directions due to magnetic field
A rough test load could be taken extrapolating from ITER: F = 0.7 MN * 1.4 = 0.98 MN
Material requirements: links connecting multilink attachments: INCONEL 718; divertor to vacuum vessel locking system: BRONZAL (Ni-Al bronze)

Table 2 collects the main needs and experts' assumption emerged from the brainstorming sessions held at the VTT Technical research centre of Finland in collaboration with CCFE and IDEAinVr lab team of create consortium.

According with Kossiakoff et al. [13], we can name this phase as a “need analysis phase”. The output of this phase is a description of the capabilities and operational effectiveness needed in the new system. In many ways, this description is the first iteration of the system itself, albeit a very basic conceptual model of the system. Although we would not yet call this description a set of requirements, they certainly are the forerunner of what will be defined as official requirements. Some communities refer to this early description as an initial capability description.

3. Manage customer needs and map them into functional requirements or input constraints

After the first needs and assumptions are gathered, according with Axiomatic Product Development Lifecycle few generic Customer Needs (CN_s) are extrapolated (level 0 of decomposition) and then they are mapped to initial functional requirements (FRis) and input constraints (ICs), Table 3.

The FRs mapped from the CN_s may not be the top level FRs, they could be children of a higher level requirement that is derived from another CN or the parent FR may not exist yet. Therefore, the FRs initially generated from the CN_s are suffixed by “i” for “initial” in order to indicate that they do not represent the FR/DP hierarchy yet.

Table 3
Customer needs.

CN ID	Statement
CN1	Lock divertor in place after placement operations, avoid displacement in any load conditions
CN2	Avoid “shaking” due to sudden change of magnetic field
CN3	To maximize reactor availability the cassette locking system should be designed to be reliable and to be remotely operated with safe margins.

Table 4 shows the FRis and ICs mapped to CN. The mapping is important to ensure requirements traceability during decomposition and zigzagging.

After CN_s are mapped to the initial FRis and ICs, the FRis should be analyzed to develop the system Functional Requirement, Design Parameters (DP), and System Components (SC) that states the system objective, the proposed system design, and the proposed system. Once the system FR/DP/SC triplet is developed, the decomposition and zigzagging process starts. The initial FRis should later be integrated into the FR/DP hierarchy where appropriate.

4. Define alternative design solutions

As the elicitation of needs and assumptions also in this stage brainstorming sessions was carried out, during which for each functional requirements some alternative design parameters and system components was proposed by fusion experts, based mainly on their knowledge and on the studies on the ITER divertor cassette locking system [8]. It was considered as reference geometry for the divertor cassette the CAD model provided by CCFE and shown in Fig. 2.

The system FRs can be developed from the analysis of the initial functional requirements (FRis) and the Input Constraints (ICs) as:

> A simple mechanism must be developed to lock the cassette to vacuum vessel. The system shall be able to taking force in any direction to avoid displacement and to avoid vibrations.

And the system DP proposed to achieve the system FR is:

> Preload the cassette in order to remove clearances, then insert tools to lock cassette in compressed position. Improve support shape to lock remaining degree of freedom.

Developing the system FR/DP/SC triplet helps ensure that a true top-down approach is used to analyse the requirements. This triplet also serves as a means to establish scope for the system and the project.

The decomposition start from this FR/DP/SC triplet. Once the parent FR and DP as well as the allocated ICs to the parent DP are given, the functions that the DP has to perform in order to achieve the parent FR and satisfy the allocated ICs are determined and they are listed as the children FRs. The decomposition and zigzagging continues by finding or developing DPs for the newly established FRs, Table 5.

For each level, we need to develop the design matrix to determine if the proposed design is an acceptable one based on the independence axiom, (4.1).

$$\begin{Bmatrix} FR\,1.1 \\ FR\,1.2 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP\,1.1 \\ DP\,1.2 \end{Bmatrix} \tag{4.1}$$

All of the ICs are first allocated to the main DP, and they should be properly allocated to the children DPs. This allocation may affect the next level decomposition because in order to satisfy the allocated ICs, we may have to introduce a new FR in the next level, Table 6.

This decomposition level 0 is not enough to define some system components yet, but it is possible to do at the next level of decomposition.

According with zigzagging principles, Tables 7 and 9 show the decomposition level 1.

To meet functional requirements 1.1.1 two alternative design parameters were proposed during brainstorming session. Both are shown in Table 7. For next decomposition both were considered

Table 4
FRi and IC.

FRi ID	FRi description	CN ID		
		1	2	3
FRi1	Remove clearances to avoid vibrations	0	X	0
FRi2	Provide an outer locking system able to take force in any direction	X	0	0
ICi ID	**IC description**			
ICi1.1	Locking System shall be compatible with remote installation and disassembly during divertor maintenance	X	X	X
ICi1.2	Simple mechanism to lock and preload in order to reduce operational time	X	X	X
ICi1.3	Locking System shall be the same for all standard cassette (left and right)	X	X	X
ICi1.4	Structural robust locking system	X	0	X

Table 5
FR-DP decomposition: level 0.

ID	FR	DP	DP type
1	A simple mechanism must be developed to lock the cassette to vacuum vessel. The system shall be able to taking force in any direction to avoid displacement	Preload cassette in order to remove clearances, then insert tools to lock cassette in compressed position. Improve support shape to lock	I
1.1	Remove any clearances to avoid vibration	Cassette preloading	II
1.2	Avoid displacement taking forces in any direction	Improve the rail and locking shape and insert tools to lock remain degree of freedom	III

Table 6
DP-IC allocations.

DP\IC	1.1	1.2	1.3	1.4
1.1	X	X	X	0
1.2	X	X	X	0

separately, the decomposition proceed in parallel, thus reaching at the end of decomposition in different solutions.

After the FR-DP decomposition is complete for this level the SCs and PVs should be developed for new DPs.

As regard the system components, different proposals were suggested during brainstorming sessions, each one is reported in Table 8 and results in a single solution.

Tables 9 and 10 show the decomposition and system components for FR/DP 1.2.

From the combinations between FRs and alternative DPs it is possible to obtain two design matrices as follows, (4.2) and (4.3):

$$\begin{Bmatrix} FR\,1.1.1 \\ FR\,1.2.1 \\ FR\,1.2.2 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ X & 0 & X \end{bmatrix} \begin{Bmatrix} DP\,1.1.1(a) \\ DP\,1.2.1(a)(b) \\ DP\,1.2.2 \end{Bmatrix} \tag{4.2}$$

$$\begin{Bmatrix} FR\,1.1.1 \\ FR\,1.2.1 \\ FR\,1.2.2 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP\,1.1.1(b) \\ DP\,1.2.1(a)(b) \\ DP\,1.2.2 \end{Bmatrix} \tag{4.3}$$

Both show an acceptable design as regard the independence axiom, since the first one is a decoupled design, the second one an uncoupled design.

Analyzing the possible combination of design parameters and system components proposed, different alternative ideas and solutions was suggested by experts involved in the brainstorming session. For three of these, it was decided to implement a CAD modeling and FEM simulation in order to have a greater perception of the feasibility of the solutions and then choose the best idea to carry on in more detail in subsequent iterations.

4.1. *Design phase in Catia*

To generate and evaluate the product concepts, a parametric CAD software, CATIA V5 of the Dassault Systemes, was used. Solutions are designed in CATIA using a top-down modeling approach in the assembly environment. Starting from a set of geometrical references of the product, the various components are designed with respect of the whole assembly, with particular attention to the relationship between the parts, in order to achieve the maximum degree of freedom making changes in further steps of the designing process. The top-down logic is a typical approach to design complex product, as stated by many authors [14,15].

Adopting a top-down approach, the designer has a complete view of the whole assembly, and is possible to make considerations and adjustments of the entire assembly in real time [16]. After the extensive work necessary to perform the CAD modeling through the top-down approach is possible to change in any time the product dimensions without any manual adjustment on the geometry, reducing time consuming [17]. All the modeling activity is performed into the Assembly Design workbench of CATIA. This module is used to create assemblies starting from scratch.

4.2. *Description of the conceived solutions*

The first solution generated during brainstorming sessions is shown in Fig. 3.

The concept idea was to preload the cassette pushing in a tool with a spherical surface. This tool is a simple mechanical tool that perform his functions only due to its shape. The spherical surface on the tool has a minor radius than the spherical surface formed on the cassette. Due to this difference in radius when inserting the tool the cassette is pushed forward, thus achieving the preload and

Table 7
FR-DP decomposition: level 1.

ID	FR	DP	DP type
1.1	Remove any clearances to avoid vibrations	Cassette preloading	II
1.1.1	Cassette preloading	(a) Insert tool to preload cassette (b) Preload cassette taking advantage of the mass of cassette	III

Table 8
DP-SC-PV mapping: level 1.

DP ID	DP Type	SC/PV ID	SC Name	PV Title
1.1	II	1.1		
1.1.1 (a)	III	1.1.1 (a)	Mechanical tool: Tool with spherical surface. Wedges arrangement. Hydraulic jack	Manufacturing and assembly processes
1.1.1 (b)	III	1.1.1 (b)	Gear arrangement. Cam arrangement	Manufacturing and assembly processes

Table 9
FR-DP decomposition: level 1.

ID	FR	DP	DP Type
1.2	Avoid displacement taking forces in any direction.	Improve the rail and locking shape and insert tools to lock remain degree of freedom.	III
1.2.1	Upgrade rail shape or insert tool to take vertical forces.	(a) Socket engagement able to take vertical forces. (b) Insert tool able to take vertical forces.	IV
1.2.2	Keep cassette in compressed position, avoid radial displacement.	Insert component after preloading able to take radial loads.	IV

Table 10
FR-DP decomposition: level 1.

DP ID	DP Type	SC/PV ID	SC Name	PV Title
1.2	III	1.2		
1.2.1 (a)	III	1.2.1 (a)	Socket engagement on support able to take vertical forces.	Manufacturing and assembly processes
1.2.1 (b)	IV	1.2.1 (b)	"I" shaped component	Purchase order
1.2.2	IV	1.2.2	"I" shaped component	Purchase order

the relative displacement of 5 mm. All the degrees of freedom are locked by the socket engagements formed on cassette and supports.

The basic principles of the operations are:

- The divertor cassette is cantilevered by the CMM (Cassette Multifunctional Mover) and moved into its position.
- The CMM rests the cassette on the support.
- Preloading of the cassette: the space between the divertor body and the outer support is filled pushing in an appropriate tool (blue piece in figure), with a spherical surface with smaller radius than the spherical surface on the cassette. The difference in radius allows to insert more easily the tool and preload the cassette.
- Due to the outer support and tool shapes the system removes clearances and withstand radial and upward forces.

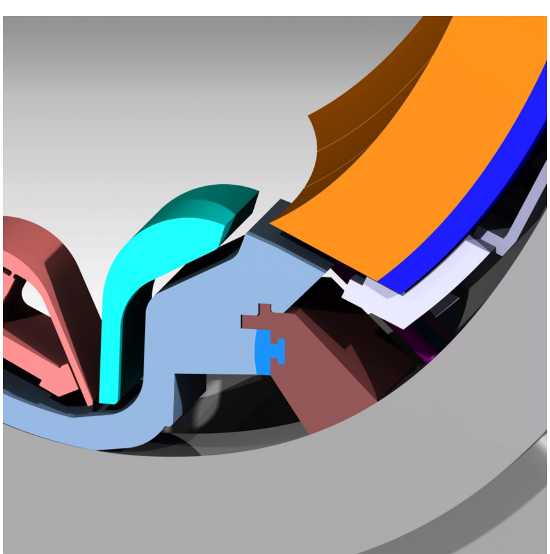

Fig. 3. Concept I.

The idea underneath the second concept was to taking advantage of the mass of cassette using a gear arrangement to preload cassette, and then insert an "I" shaped tool able to withstand vertical and radial loads. The solution is shown in Fig. 4.

The basic principles of the operations are:

- The cassette slides toroidally in the vessel slightly raised from the support.
- When it is in position the cassette leans on the support and due to its shape and the "rack and pinion" system the cassette is preloaded, so taking advantage of the weight of cassette and "helping" rotation by means of a RH tools.
- When the cassette is preloaded a tool could be inserted to lock the cassette.

A future assessment will demonstrate if the weight is enough to provide the force required to preload the cassette, or if will be

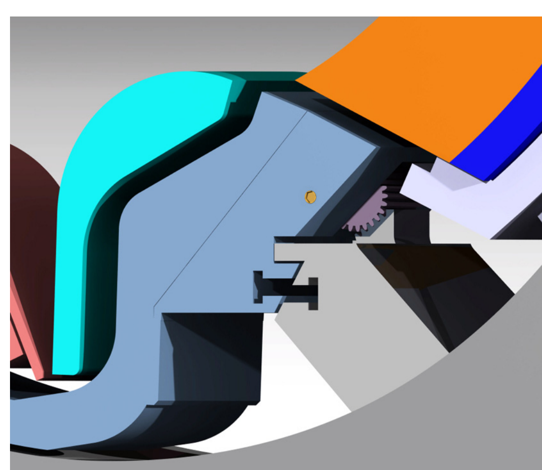

Fig. 4. Concept II.

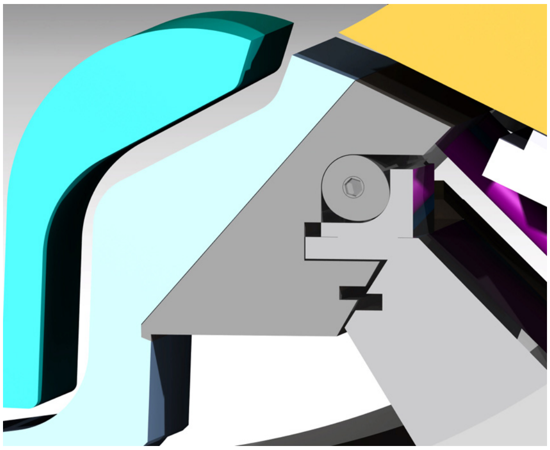

Fig. 5. Concept III.

necessary to combine the contribute of the weight with a rotation of gear by means of a remote handling tool.

As well as in the solution II also in third solution is exploited the mass of the divertor, using a "cam" arrangement instead of the gear ones. The principle of operation is the same as the previous solution, Fig. 5.

The three solutions presented were not the only ones developed during the work of generation of conceptual alternatives, but these three were the ones selected by the experts during the brainstorming sessions as the most promising and feasible. A rough FEM model to a better understanding of structural feasibility and as support to the subsequent evaluation stage was carried out on this three concepts.

5. Preliminary FEM analyses

A FEM analysis was carried on for each solution as a support to evaluation phase, to better understand the load distribution and as a more objective ways to evaluate the structural robustness of the different solutions. A FEM analysis is also a way to refine structural and material requirements [18], and provide a first idea about the necessary thickness and dimensions to withstand the high loads as extrapolated from ITER load cases.

FEM analyses were carried out using ANSYS Workbench, release 14. The model designed in CATIA V5 was imported and the different contact areas have been appropriately defined. Some contacts are simulated as "bonded", some others as "frictional", whereby were performed contact non-linear analysis. ANSYS employs the "Newton-Raphson" approach to solve nonlinear problems. In this approach, the load is subdivided into a series of load increments. The load increments can be applied over several load steps. Before each solution, the Newton-Raphson method evaluates the out-of-balance load vector, which is the difference between the restoring forces (the loads corresponding to the element stresses) and the applied loads. The program then performs a linear solution, using the out-of-balance loads, and checks for convergence. If convergence criteria are not satisfied, the out-of-balance load vector is re-evaluated, the stiffness matrix is updated, and a new solution is obtained. This iterative procedure continues until the problem converges.

The model was than discretized, the number of elements of the mesh and the edge division have been chosen such as to capture the singularity of the model with a good approximation but without an excessive level of detail, as required by the purely conceptual design phase.

The element used to mesh the solid model is the SOLID186, a higher order 3-D 20-node solid element that exhibits quadratic displacement behaviour. The element is defined by 20 nodes having three degrees of freedom per node: translations in the nodal *x*, *y*, and *z* directions.

Contacts were simulated using elements TARGE170 and CONTA174. TARGE170 is used to represent various 3-D "target" surfaces for the associated contact elements. The contact elements themselves overlay the solid, shell, or line elements describing the boundary of a deformable body and are potentially in contact with the target surface, defined by TARGE170.

CONTA174 is used to represent contact and sliding between 3-D "target" surfaces (TARGE170) and a deformable surface, defined by this element. The element is applicable to 3-D structural and coupled field contact analyses.

Regarding the loads, was considered the case SL-1 + VDEII fast down + MFD-II + NOP (Category III) (Table 1).

The forces were applied transforming them in pressure on surfaces, and moments are applied as two parallel forces in opposite. Fig. 6 shows the imported geometry and the loads applied to the three solutions. As regard the post-processing phase, equivalent Von-Mises stress is shown in Fig. 7, and the obtained safety factor with reference to equivalent stress is shown in Fig. 8. The results are also collected in Table 11.

Table 11
FEM analysis results.

	$\sigma_{eq,max}$ [MPa] (Von Mises)	Safety factor
Concept I	149.69	1.67
Concept II	123.88	3.26
Concept II	219.58	2.14

6. Concept evaluation using Fuzzy-AHP

Concept evaluation was carried out by means of Fuzzy-AHP. Two different teams of experts were involved in the evaluation: First, the "DTP-2" team at VTT technical research centre of Finland was asked to fill the first section of the questionnaire. It was the section about the "preference" in which the selected evaluation criteria were pair-wise compared. The chosen criteria are shown in Table 12:

According with the IPADeP (Fig. 1), during this first iteration as much as possible "high-level" evaluation criteria were considered, with the highest level of abstraction. They are based mainly on the functions of the locking system, Decision makers answer their preference about the criteria using Fuzzy Linguistic Variables shown in Table 13:

Table 12
Evaluation criteria.

ID	Criteria
C1	Simplicity (mechanical and of operation)
C2	Structural Robustness
C3	Ability to preload cassette

Table 13
Fuzzy linguistic variables.

Linguistic scale for importance	Abbreviation
Absolutely more important	AMI
Very strongly more important	VSMI
Strongly more important	SMI
Weakly more important	WMI
Equally important	EI
Weakly less important	WLI
Strongly less important	SLI
Very strongly less important	VSLI
Absolutely less important	ALI

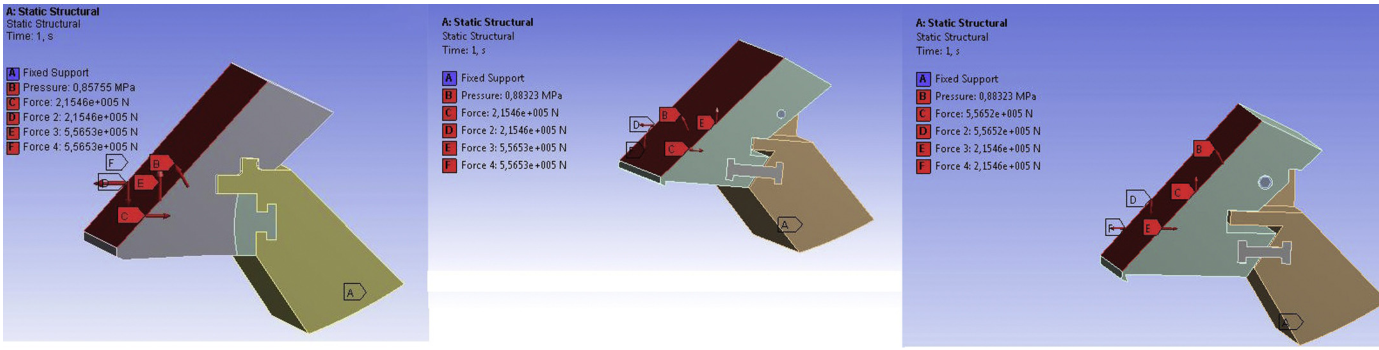

Fig. 6. Geometry and loads—concepts I, II and III.

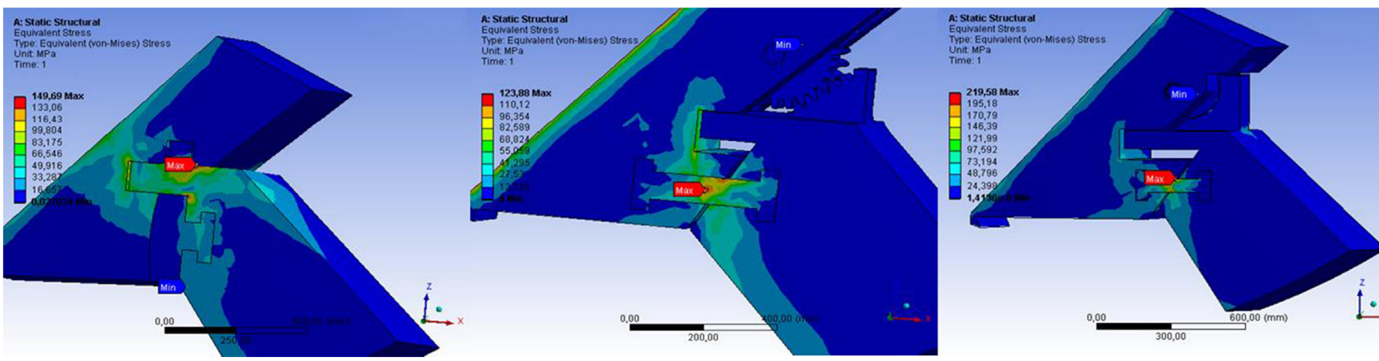

Fig. 7. Equivalent Von-Mises stress concepts I, II and III.

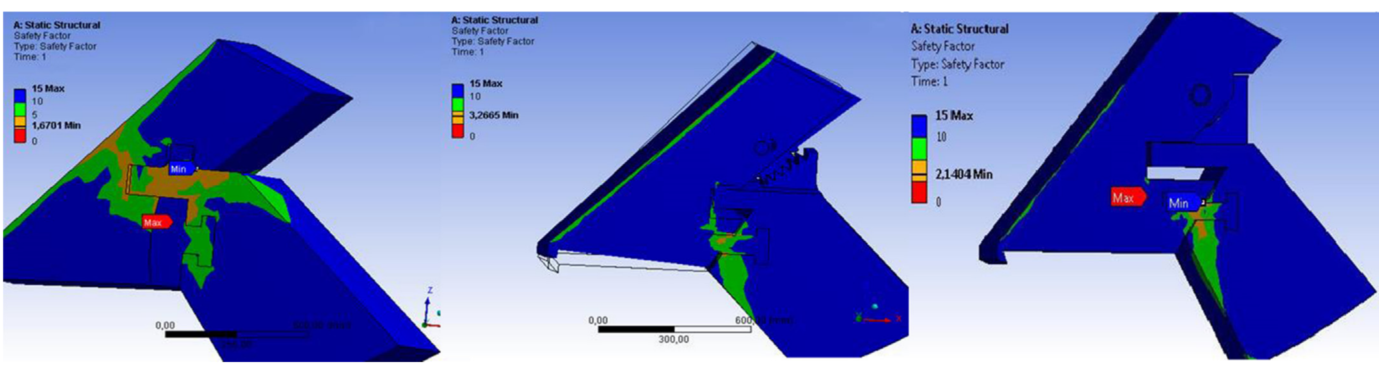

Fig. 8. Safety factor concepts I, II and III.

Transforming the results obtained into triangular Fuzzy numbers, getting the average values and applying the extent analysis the weight vector with respect to the decision criteria C1, C2, C3 was obtained (Fig. 9):

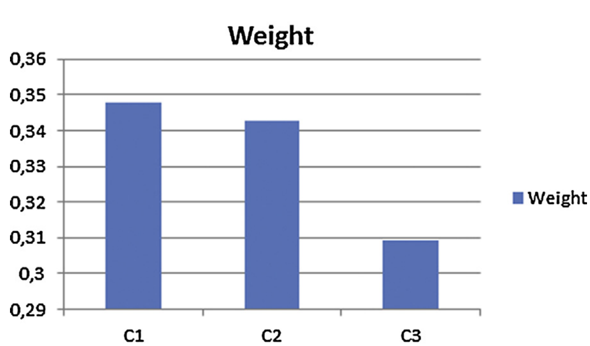

Fig. 9. Criteria weights.

$W = (0.3477; 0.343; 0.309)$

Then the pair wise comparison among conceptual alternatives was carried out in IDEAinVR Lab at the University of Naples "Federico II"—Department of Industrial Engineering [19], where a team of engineers was asked to compare the alternatives with respect of each criteria using the fuzzy linguistic variables shown in Table 14.

Table 14
Fuzzy linguistic variables.

Linguistic scale for importance	Abbreviation
Absolutely Better	AB
Very strongly Better	VSB
Strongly Better	SB
Weakly Better	WB
Equally good	EG
Weakly worse	WW
Strongly worse	SW
Very strongly worse	VSW
Absolutely worse	AW

Fig. 10. Concepts evaluation in VR Lab.

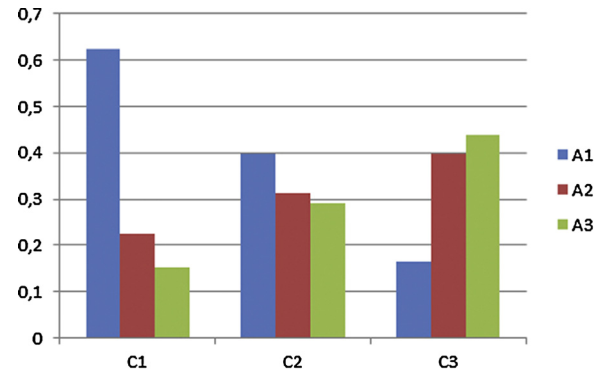

Fig. 11. Results for each evaluation criteria.

Table 15
Alternatives pair-wise comparison with respect of C1.

C1	A1	A2	A3
A1	(1,1,1)	(1,33; 1,76; 2,22)	(1,29; 1,72; 2,17)
A2	(0,45; 0,57; 0,75)	(1,1,1)	(0,81; 1,14; 1,55)
A3	(0,46; 0,58; 0,78)	(0,65; 0,88; 1,23)	(1,1,1)

Table 16
Alternatives pair-wise comparison with respect of C2.

C2	A1	A2	A3
A1	(1,1,1)	(0,92; 1,24; 1,6)	(0,9; 1,22; 1,61)
A2	(0,63; 0,81; 1,09)	(1,1,1)	(0,75; 1,08; 1,51)
A3	(0,62; 0,82; 1,11)	(0,66; 0,93; 1,33)	(1,1,1)

Table 17
Alternatives pair-wise comparison with respect of C3.

C3	A1	A2	A3
A1	(1,1,1)	(0,53; 0,67; 0,9)	(0,45; 0,58; 0,79)
A2	(1,11; 1,49; 1,89)	(1,1,1)	(0,68; 0,99; 1,42)
A3	(1,27; 1,72; 2,22)	(0,7; 1,01; 1,47)	(1,1,1)

Table 18
Results for each evaluation criteria.

criterion	A1	A2	A3
C1	0.623	0.225	0.151
C2	0.397	0.312	0.289
C3	0.163	0.398	0.437

The two concepts were shown on two different screens together with the two simulations realized Fig. 10.

Getting the average values of the results obtained by the questionnaire the following Fuzzy evaluation matrices are obtained, Tables 15–17:.

Then, applying the extent analysis, these matrices are used to estimate weights, in this case weights of each candidate under each criterion separately. The results are given in Table 18 and Fig. 11.

Finally, adding the weights per candidate multiplied by the weights of the corresponding criteria, a final score is obtained for each candidate. Table 19 shows these scores.

According to the final scores, it is clear that Concept I is the preferred alternative. Therefore, the Concept I will be the starting point for the further decomposition and next iterations of IPADeP. It will become more detailed in each iteration and will be adapted to meet any new requirements.

Table 19
Final scores.

	A1	A2	A3
Final scores	**0.40382**	0.3087	0.2874

7. Conclusions

The work was focused on conceptual design stage in DEMO divertor-to-vacuum vessel locking system. Due to the early nature of design activities on DEMO, requirements are still uncertain and incomplete. For this it was first proposed an enhanced design process for drafting solutions in an incomplete requirements environment. The process proposed, called IPADeP (Iterative and Participative Axiomatic Design Process), is based on the Axiomatic Product Development Lifecycle, and it is consistent with ISO/IEC 15288-"Systems and software engineering". It is an iterative and incremental design process, participative and requirements driven. IPADeP aims to propose a systematic manner to achieve solutions in the initial phase of conceptual design stage in complex situations, limiting the risks arising from the lack of requirements and proceeding iteratively, refining and completing the requirements at each iteration. According with this process some solutions for DEMO divertor locking system were proposed and generated with the help of a CAD software. Then it was carried on a FEM analysis as a first objective evaluation and to support the evaluation process conducted following the Fuzzy-Analytic Hierarchy Process (F-AHP) method. Two experts teams were involved during the requirements elicitation, concepts generation and concepts evaluation: "DTP-2" team in VTT Technical research centre of Finland and ENEA and IDEAinVR team of CREATE Consortium. In particular, three concepts were generated, analysed and then pair-wise compared in Virtual Reality Lab of University of Naples Federico II–DII; where it was possible to have a simultaneous vision of the two solutions showing them on two different screens, and involving several experts. Taking into account the results from FEM analysis and Fuzzy-AHP, the final concept chosen will be further detailed in future studies. The optimal concept selected in this work represents the starting point for the following IPADeP iterations, in which the decomposition will proceed to more detailed levels and requirements will be completed. At the end of the process a system requirements document (SRD) will be completed, a detailed design of locking system will be available and it will be possible to proceed with Verification and Validation activities.

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