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Design progress of the DEMO divertor locking system according to IPADeP methodology

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Abstract

The Iterative and Participative Axiomatic Design Process (IPADeP) deals with the early conceptual design stage of complex mechanical assemblies. It provides a systematic approach based on the theory of Axiomatic Product Development Lifecycle and aims to minimize the risks related to the uncertainty and incompleteness of the requirements, considering that the requirements will be refined and completed during the process. IPADeP has an iterative nature and is focused on the experience of the people involved in the design process. The functional requirements and the design parameters are conceived through brainstorming sessions and the concept selection is performed involving several experts through a Multi Criteria Decision Making technique. IPADeP has been adopted as methodology to address the early conceptual design stage of a subsystem of the DEMOnstration fusion power plant: the divertor cassette-to-vacuum vessel locking system. A first iteration was performed, resulting in the selection of a "high level" rough solution. According with IPADeP this paper presents an improvement of this solution, performing a new iteration of the process, since the system is ripe to proceed with the decomposition and zigzagging to the second level and new requirements are coming in from the development of the interfaced systems.

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Keywords: IPADeP, Axiomatic Design, Conceptual Design, fusion engineering

1. Introduction

Early conceptual design stage, dealing with an high level of abstraction, is the most crucial task in an engineering product development lifecycle [1]. Recent researches have shown that the top cause of troubled projects regards the early design stage and is related to the requirements that sometimes are unclear, imprecise, with lack of agreement and priority [2]. This imprecise and incomplete knowledge of the design requirements make also difficult to utilize computer-based system or prototypes during the early phase of product lifecycle [3]. However, such systems would assist to deal with conceptual design issues that are highly interdisciplinary and often involve collaboration of stakeholders, partners and engineers various and geographically dispersed. The impact of making good decisions early in the product life cycle is very high, and declines as the design matures. The best opportunities exists in the preliminary design stage (Fig. 1) [4]. The concepts generated at this stage affect the basic shape generation and material selection. In the detailed design phase, it becomes difficult to correct shortcomings associated with a conceptual design stage addressed incorrectly and unsystematically.

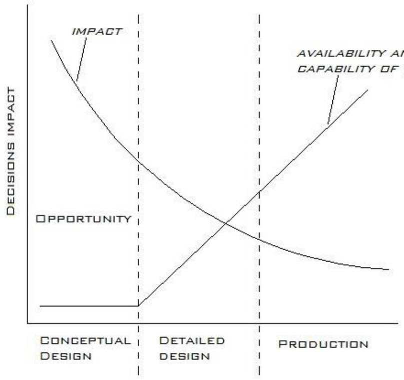

Fig. 1 Design maturity vs opportunity

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In this context, so-called principle-based methods have gained popularity because they provide a general scientific basis that supports design decisions. In particular, studies of the early design stages dealing with a higher level of abstraction have recently attracted increasing attention from academia [5].

The Product development lifecycle (PDL) models should support this phase proposing a systematic approach to deal with design starting from the very early stage, identifying correct and complete requirements and verifying the design. The traditional practice of systems engineering management involves the determination of requirements at or near the beginning of a system development project. All subsequent steps are dependent upon the completeness, accuracy and specificity of these requirements. Consistently with the Systems Engineering approach [6] the Iterative and Participative Axiomatic Design Process (IPADeP) [7] provides a systematic approach based on the theory of Axiomatic Product Development Lifecycle (APDL) [8]. It aims to optimize the collaboration among the parties involved in complex interdisciplinary projects during the early stage of design and to minimize the risks related to the uncertainty and incompleteness of requirements. Since at the conceptual stage information is very fuzzy and incomplete, making the design process quite difficult and challenging, IPADeP proposes an iterative process focused on the experience of the people involved and deals with the decision making phase using a multicriteria decision making technique (MCDM) which takes into account the " fuzzy" nature of the information: Fuzzy – Analytical Hierarchy Process (AHP) [9, 10].

IPADeP has been adopted as methodology to address the early conceptual design stage of a subsystem of the DEMOnstration fusion power plant (DEMO) [11]: the divertor cassette to vacuum vessel locking system [12]. A high level rough solution was conceived. According with IPADeP this paper presents the design progress of this component, proceeding with the decomposition and zigzagging towards the second level of the design, considering also that new requirements are coming from the development of the interfaced systems.

2. IPADeP

The IPADeP flowchart is presented in Fig. 2. Based on the APDL it was developed according to the design process roadmap proposed by Tate and Norlund [13] to propose a systematic thinking to support design activities in the early conceptual design stage. It is an iterative incremental design process, participative and requirements driven.

IPADeP aims to drive the conceptual design activities avoiding traditional design-build-test-redesign cycle. It integrates brainstorming sessions, MCDM techniques and the Axiomatic Design (AD) method [14], taking advantages of his systematic and logic approach for derive, documenting and optimizing the designs. Furthermore it proposes the use of CAD and simulation software from the early stage to improve idea generation and communication among stakeholders.

IPADeP highlights the iterative nature of the design activities and the central role of the "human factor", with the involvement of experts' panel during the requirements elicitation and concept evaluation. The uncertainty of the information during the early stage is considered proceeding level by level towards a detailed solution and using Fuzzy-AHP during the decision making phase. Concept selection is a complex task for engineering designers as it can be considered as the most critical decision-making step in the product development process [15]. During this phase, erroneous solutions need to be minimized, which means that several facets of the problem have to be considered concurrently. Fuzzy AHP allows dealing with the multicriteria decision making stage considering uncertainties related to the early stages of design and to the judgements of the decision makers. It consists of two different phase. A first stage concerns the weighting of the evaluation criteria. A questionnaire is submitted to experts to pairwise compare the criteria, asking questions like: "which of Ci and Cj is more important, and by how much (how many times)?"

The second stage concerns the weighting of the alternative design options. A second questionnaire is submitted to a different team of experts, asking to pairwise compare the alternatives with respect of each criterion by questions like: "How good is the Alt.i when it is compared to Alt.j as regard the criterion Cj?"

In both stage the evaluation took place by ten linguistic terms (absolutely more important, very strongly more important, strongly more important, weakly more important, equally important, weakly less important, strongly less important, very strongly less important, absolutely less important) corresponding to fuzzy numbers. These fuzzy numbers are then processed according to the extent analysis [9] to achieve the weights of each solution and identify the best solution. An extended presentation of the method is contained in [7].

3. Design Progress of DEMO divertor cassette to vacuum vessel locking system.

3.1. First iteration

IPADeP was used to deal with the conceptual design of the DEMO divertor cassette to vacuum vessel locking system. The main aim of the divertor locking system within a fusion reactor is to keep locked the divertor in its relative position to the vacuum chamber (named Vacuum Vessel, green in Fig. 5), withstanding the electromagnetic and neutral forces and avoiding vibrations.

The first iteration of the design process (Fig.2) was performed and the results were presented in [12]. Meetings and discussions were carried out with experts and stakeholders to understand the different needs that DEMO divertor locking system shall meet. Then customer needs (CNs) were analyzed and few "high level" Functional requirements (FRs) and input constraints (ICs) were derived. Proceeding according with AD, Design Parameters (DPs) were defined for each FR, consistently with the

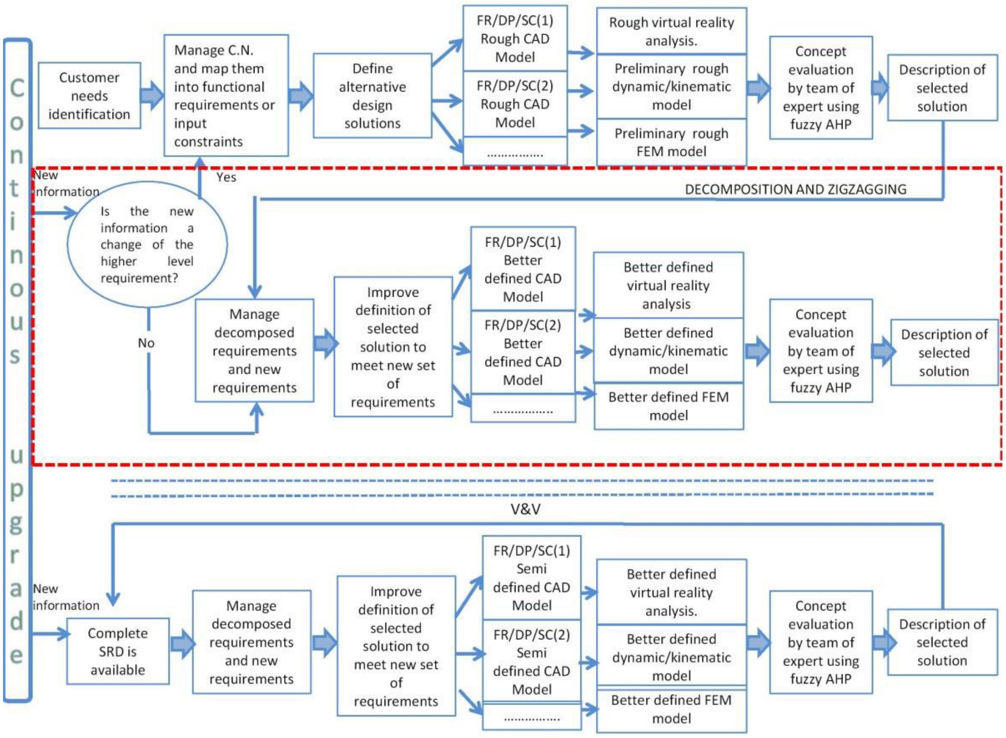

Fig 2 IPADeP scheme [7]

independence axiom [16]. Templates as proposed by Gumus [17] were used to improve communication and traceability. The design parameters were implemented in CAD models, and three solutions were proposed and analyzed using a Finite Elements Method (FEM) model. These solutions were finally evaluated submitting a questionnaire to an experts' panel according to the Fuzzy-AHP technique. The concepts were pairwise compared showing CAD models and FEM analysis to the team of experts at the IDEAinVR Lab of CREATE Consortium/University of Naples Federico II (Fig. 3) [18].

Fig 3 Concepts evaluation at IDEAinVR Lab [12]

The evaluation resulted in the selection of an optimal conceptual solution (Fig.4), which has been the starting point for the next iteration here presented. The idea behind this solution is to preload the cassette pushing in a tool with a spherical surface, in order to avoid cassette vibration. This tool is a simple mechanical tool that performs 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 the relative displacement of 5mm. All the degrees of freedom are locked by the socket engagements formed on cassette and supports.

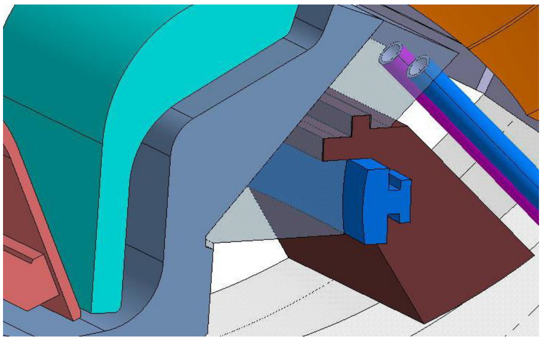

Fig 4 Concept selected during first iteration [12]

Table 1 Divertor locking system requirements

First iteration requirements	**Second iteration requirements**
General requirements	
Deliver high availability	
Be flexible to new or changed task requirements	
Deliver High quality operation	
Perform operation safely	
Feasibility and reliability of the plant maintenance system	
Reference model: DEMO divertor 2013	Reference model: DEMO divertor 2014
	The divertor shall be replaced during DEMO operational life (TBD the number of times or frequency).
	The design shall provide a mean for rapid replacement and refurbishment.
	These cassettes shall be inserted radially through a lower level port and moved toroidally before being locked into position (TBC).
	The path for gas conductance from the divertor sub-volume to the main chamber shall be minimized by maintaining close proximity of the divertor cassette to the vacuum vessel, and by a proper design of the cassette locking system.
Interface requirements	
Iter-like solution at the inner side	
Remote handling compatibility	
	The attachment of the divertor cassette can be on the Vacuum Vessel (VV).
	The Divertor will interface with the In-Vessel remote handling tools and fixtures. The Divertor will have sufficient clearance for installation, maintenance and replacement of all components.
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	The support system of the cassette to the inner and outer shall withstand the electromagnetic loads that are specified in the Load Specifications Divertor Cassette [19]
	The support system of the cassette to the inner and outer shall provide a plasma-facing surface alignment that is within a tolerance of (TBD) (for ITER is ±1.5 mm).
	The support system of the cassette to the inner and outer shall be designed to accommodate distortions of the cassette that are caused by thermal bowing, neutron-induced swelling, and application of vacuum.
	Dead weight : 17.2 ton
Electrical requirements	The cassette shall be electrically connected to the vacuum vessel via the inner and outer locking system (TBC). This locking system shall be designed to carry the maximum halo and eddy currents in case of VDEs.
Material requirements	
Divertor to vacuum vessel locking system: BRONZAL (Ni-Al bronze).	The materials properties are described in the DEMO Materials Properties Handbook (EFDA_D_tbd).
Functional requirements	
Lock/ unlock cassette in place	
Preload cassette in order to remove clearances	The Divertor cassette to vacuum vessel locking system shall be pre-loaded TBC, or designed to minimize any dynamic effect during off-normal events. If used during assembly of the Divertor, bolts shall be secured (lock welding or equivalent).

3.2 Second iteration

The second level of the design (highlighted in the red box in Fig. 2) was mainly driven by the new information (overall dimensions, shape, interfaces) that came from the development of interfaced components. In detail, several progress on DEMO divertor and DEMO Vacuum Vessel were performed, resulting in new interface requirements [20]. Moreover new, updated, CAD models of the Divertor and Vacuum Vessel were released (Fig. 5). These models were used as new input for the design. From the new reports published on the interfaced components [19, 20] new requirements for the locking system were elicited. Table 1 collects the “first level” and “second level” requirements. The first level requirements were the starting point for the first iteration of the design process, as presented in [7, 12]. The second level requirements represent substantially more accurate definitions of the previous requirements, or new interface indications coming forth from the development of the interfaced components.

A team of experts was involved in the analysis of the new requirements. The new information were not in conflict with the “higher level” assumptions and the solutions evaluated in the previous iteration result then suitable to these new information.

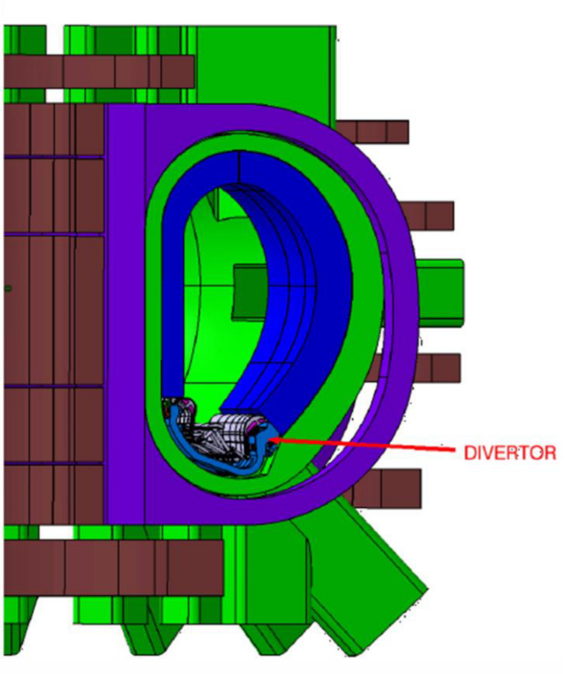

Fig 5 DEMO VV and divertor models (2014)

Basing on new requirements, Customer needs (CNs) were re-evaluated and a new CN was added to the previous table (CN4 - Table 2).

Table 2. 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.
CN4	*Accommodate distortions*

The new CN led to new FRs and DPs. Table 3 shows the initial functional requirements (FRis- they do not represent the FR/DP hierarchy yet) and Input Constraint (ICs) mapped to CN (italic type is used for the FRs and ICs added during second iteration). The mapping is important to ensure requirements traceability during decomposition and zigzagging. Starting from these FRis and ICis the decomposition and zigzagging proceed to the definition of design parameters and system components, which define new design solutions.

During the second iteration the decomposition was carried out in compliance with the new FRis and ICs. The results of the first iteration were used as reference for the new design.

Table 3 FR - IC mapping

FRi ID	FRi description	CN ID			
		1	2	3	4
FRi1	Remove clearances to avoid vibrations	0	X	0	0
FRi2	Provide an outer locking system able to take force in any direction	X	0	0	0
FRi3	*Provide a system to accommodate distortions*	*0*	*0*	*0*	*X*
ICi ID	IC description				
ICi1.1	Locking System shall be compatible with remote installation and disassembly during divertor maintenance	X	X	X	0
ICi1.2	Simple mechanism to lock and preload in order to reduce operational time	X	X	X	0
ICi1.3	Locking System shall be the same for all standard cassette (left and right)	X	X	X	X
ICi1.4	Structural robust locking system	X	X	X	X
ICi1.5	*Geometry and interface consistent with Divertor CAD model 2014*	*X*	*X*	*X*	*X*
ICi1.6	*Dead weight 17.2 ton*	*X*	*X*	*0*	*0*

Keeping good documentation and traceability, this kind of approach helps to optimize in any phase the information available, avoiding redesign cycle. Table 4 shows the updated FRs and the DPs up to the second level of decomposition and Fig. 6 summarize decomposition and zigzagging process for the FR 1.1.

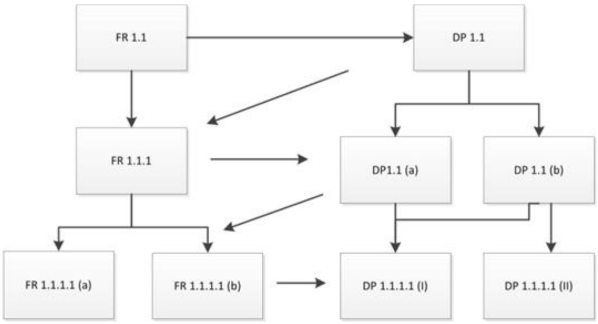

Fig. 6 FR- DP 1.1 Decomposition and zigzagging

The complete decomposition level 1, including system components, CAD models and FEM analysis, are reported in [12]. Equations (1) and (2) show the decoupled Design matrix at level 1. Equations (3) and (4) show the partially coupled design matrix at the second level.

Design solutions came out of the decomposition was mainly an improvement of the previous solutions to meet new requirements FRi3 and the input constraint ICi1.5 and ICi1.6.

Table 4 Decomposition level 2

Level	ID	FR	DP
0	1.1	Remove any clearances to avoid vibrations	Cassette preloading
I	1.1.1	Preloading the cassette	(a) Insert tool to preload cassette (b) Preload cassette taking advantage of the mass of cassette
II	*1.1.1.1*	*(a) Insert tool to preload cassette* *(b) Preload cassette taking advantage of the mass of cassette*	*(I)Transports the divertor on a tilted rail slightly raised from the rest position. Releasing the divertor it moves forward due to the inclination of the rail, preloading the cassette. The surface of the divertor should have a spherical shape to ease the preload. Insert a removable hydraulic jack to help the preload.* *(II) Cam arrangement to preload cassette taking advantage of the mass*
0	1.2	Avoid displacement due to forces in any direction.	Improve the rail and locking shape and insert tools to lock remain degree of freedom.
I	1.2.1	Lead vertical forces through to the rail or insert tool to take vertical forces.	(a) Socket engagement able to take vertical forces. (b) Insert tool able to take vertical forces.
II	*1.2.1.1*	*(a) Withstand vertical forces through a socket engagement on the rail.* *(b) Insert tool able to take vertical forces.*	*(I) Socket engagement with spherical shape on the rail to accommodate the sphere shaped on the cassette* *(II) insert an I-shaped tool take vertical forces*
I	1.2.2	Keep cassette in compressed position, avoid radial displacement.	Insert component after preloading able to take radial loads.
II	*1.2.2.1*	*Withstand radial loads*	*(I) Shaper the socket engagement in a way to keep cassette in compressed position* *(II) use the I-shaped tool to keep cassette compressed*
0	*1.3*	*Provide system to accommodate distortions*	*Allow small rotations around the tangential axis*
I	*1.3.1*	*Allow small rotation around the tangential axis*	*(a)Modular composition of the locking system allowing small relative rotation of 2 modules* *(b) Leave gap at the socket engagement to allow small rotation*
II	*1.3.1.1*	*(a)Modular composition of the locking system allowing small relative rotation of 2 modules* *(b) Leave gap at the socket engagement to allow small rotation*	*(I) Joint two modules by a hinge axis so as not to constraint the rotation* *(II) Allow rotation at the spherical socket engagement.*

$$\begin{Bmatrix} FR1.1.1 \\ FR1.2.1 \\ FR1.2.2 \\ FR1.3.1 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ X & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP1.1.1(a) \\ DP1.2.1(a)(b) \\ DP1.2.2 \\ DP\ 1.3.1(a)(b) \end{Bmatrix} \quad (1)$$

$$\begin{Bmatrix} FR1.1.1 \\ FR1.2.1 \\ FR1.2.2 \\ FR\ 1.3.1 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP1.1.1(b) \\ DP1.2.1(a)(b) \\ DP1.2.2 \\ DP1.3.1 \end{Bmatrix} \quad (2)$$

$$\begin{Bmatrix} FR1.1.1.1\ (b) \\ FR1.2.1.1(a) \\ FR1.2.2.1 \\ FR1.3.1.1(b) \end{Bmatrix} = \begin{bmatrix} X & X & 0 & 0 \\ 0 & X & X & X \\ 0 & 0 & X & X \\ 0 & 0 & X & X \end{bmatrix} \begin{Bmatrix} DP1.1.1.1(I) \\ DP1.2.1.1(I) \\ DP1.2.2.1(I) \\ DP1.3.1.1(II) \end{Bmatrix} \quad (3)$$

$$\begin{Bmatrix} FR1.1.1.1\ (a) \\ FR1.2.1.1(b) \\ FR1.2.2.1 \\ FR1.3.1.1(a) \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & X & 0 \\ 0 & X & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP1.1.1.1(II) \\ DP1.2.1.1(II) \\ DP1.2.2.1(II) \\ DP1.3.1.1(I) \end{Bmatrix} \quad (4)$$

The solutions arising from the combination of DP result consistent with the independence axiom.

In particular from the analysis performed on the concepts generated during the first iteration it was decided to integrate the two design parameters 1.1.1, conceiving a solution in which a spherical surface and the mass of the divertor contribute to preload and lock the cassette, allowing system rotation in order to accommodate distortions. Fig. 7 shows the model of this first solution, which integrate DP 1.1.1.1 (I), DP 1.2.1.1 (I) and DP 1.3.1.1 (II). In this solution the divertor is transported on a tilted rail slightly raised from the rest position. Releasing the divertor it moves forward due to the inclination of the rail, preloading the cassette. The surface of the divertor should have a spherical shape to ease the preload and allow rotation due to thermal expansion.

Moreover the “CAM arrangement” (Fig. 8) [12] design was re-evaluated in the view of the new requirements. It consists in a cam arrangement to take advantage of its own mass to preload the cassette. When the cassette leans on the support the cam system pushes it forward applying the requested preload. Then an I-shaped tool is inserted to lock the cassette.

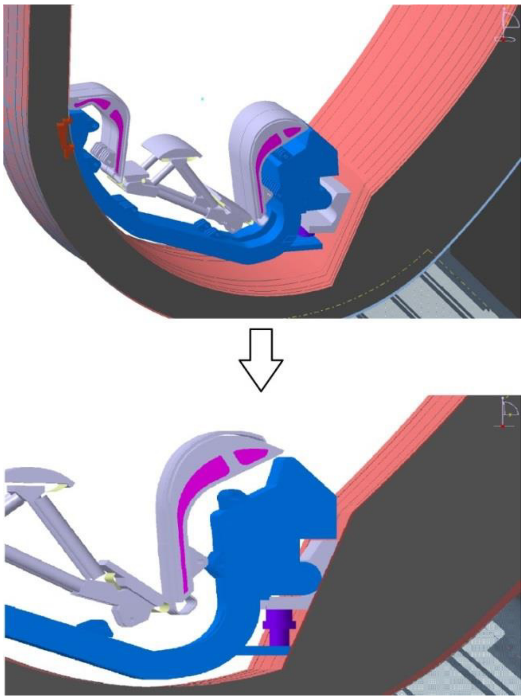

Fig.7 New "second level" solution

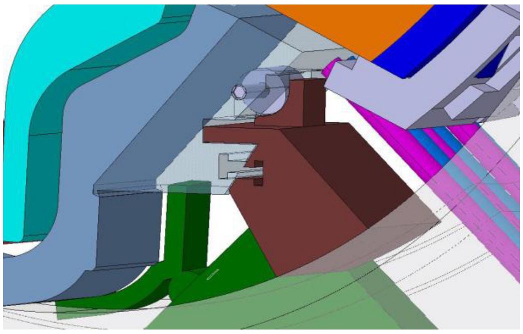

Fig. 8 Cam arrangement solution

Kinematic analyses were performed for each solution, in order to verify and compare them from the kinematic point of view.

The new "second level" solution was compared to the concept selected during the first iteration and the "cam arrangement" using the Fuzzy- AHP [12]. A team of 8 experts was asked to answer a first section of a questionnaire about the "preference", in order to obtain the evaluation criteria weights. The chosen criteria and the weights are listed in Table 5.

Table 5 Evaluation criteria

ID	Criteria	Weight
C1	Simplicity (mechanical and of operation)	0.35
C2	Structural Robustness	0.34
C3	Ability to preload cassette	0.30
C4	Option of allowing distortions	0.30

The pair wise comparison among conceptual alternatives was carried out in IDEAinVR Lab at the University of Naples "Federico II"- Department of Industrial Engineering, where a team of 25 engineers compared the alternatives with respect of each criterion, filling the second section of the questionnaire. The results of the questionnaire has been processed using the extent analysis [9], achieving the final score (Table 6).

Table 6 Final scores

	A1 (Fig. 4)	A2 (Fig.8)	A3 (Fig. 7)
	(I level concept)	(cam arrangement)	(II level concept)
Final Scores	0.35	0,33	**0,41**

The new "second level" concept was the preferred solution, and represents the chosen concept design. It will be the starting point for the third iteration.

4. Conclusions

The work presents the design progress of the DEMO divertor cassette-to-vacuum vessel locking system, focusing on the design process adopted.

IPADeP, basing on the AD theory, provides a systematic approach to address the early stage of the design, dealing with the uncertainty of the information. It improves the traceability and documentation of the design activities. Moreover proceeding iteratively layer by layer it allows an easy integration of the new requirements and subsequents Design Parameters, avoiding redesign cycles.

These IPADeP characteristics has been proved within the conceptual design activities of DEMO divertor locking system.

The design started from few high level requirements, which led to some "high level" conceptual solutions. This concepts were evaluated using the Fuzzy – AHP technique, in order to take into account the "fuzzy" nature of the information at this stage.

In this work a second level of decomposition has been presented, basing on the updated requirements from the interfaced components. The intergation of this new requirements in the design did not result in difficulties or redesign cycle, thanks to the iterative and incremental IPADeP approach, that provides a design process that starts from an high level of abstraction to proceed step by step towards a detailed solution.

The locking system solutions came out from this second iteration will be the starting point for a third iteration , to be performed as far as new requirements will be elicited. Moreover, further studies about the IPADeP application in "critical contests" shall be performed, in order to enhance its characteristics and validity.

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