Iterative and Participative Axiomatic Design Process in complex mechanical assemblies: case study on fusion engineering

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Abstract The present paper proposes a structured Product Development Lifecycle (PDL) model to deal with the concept design stage of complex assemblies. The proposed method provides a systematic approach to design, aimed to improve requirements management, project management and communication among stakeholders as well as to avoid project failures reducing project development time. This research also provides suggestions and recommendations for utilizing different analysis, synthesis and assessment methodologies along with the proposed approach. The process developed, named Iterative and Participative Axiomatic Design Process (IPADeP), is consistent with ISO/IEC 15288: 2008 – "Systems and software engineering", and INCOSE Systems engineering handbook. It is an iterative and incremental design process, participative and requirements driven, based on the theory of Axiomatic Product Development Lifecycle (APDL). IPADeP provides a systematic methodology in which, starting from a set of experts' assumptions, a number of conceptual solutions are generated, analysed and evaluated. Based on the results obtained, new iterations can be performed for each level of decomposition while product requirements are refined. In this paper, we applied IPADeP to the initial phase of conceptual design activities for DEMO divertor-to-vacuum vessel locking system in order to propose new innovative solutions.

Keywords Systems engineering · Concept design · Axiomatic Design · Fuzzy-AHP · DEMO divertor locking system

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1 Introduction

Engineering product development is becoming increasingly knowledge-intensive and collaborative. The stakeholders and partners involved in product development are increasing various and geographically dispersed, so more and more attention is paid to global cooperation during the design phase and outsourcing the manufacturing processes [1]. 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 [2].

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, with lack of agreement and/or priority, contradictory, ambiguous and imprecise [3]. These situations are common at the beginning of the design process (especially before detailed design as defined by Pahl and Beitz [4]), due to numerous experts involved in integrated and collaborative design [5].

The PDL models should support this phase identifying correct and complete requirements and verifying the design starting from the very early stages in order to reduce the cost and schedule and to satisfy the customer since 80% of the products total cost is committed during the concept development phase [6]. Requirements management concerns the collection, analysis, and validation of requirements with all the communications and negotiations inherent in the working process. Without establishing detailed requirement, the risk of project failure would be unacceptably high. For this reason it is extremely important to make a systematic approach to design since the early phase of product development process. Indeed during this phase the loss caused by selecting wrong design solutions can afflict the whole development processes and is hard to recover later [2].

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. Within the context of ISO/IEC 15288:2008 and INCOSE Systems engineering handbook [7], requirements are specifically mentioned in two of the technical processes and they are drivers for many of the system life cycle processes. Depending on the system development model, requirements capture may be done nominally once near the beginning of the development cycle or, as for agile methods, be a continuous activity. When applying systems engineering, there is near unanimous agreement that successful projects depend on meeting the needs and requirements of the customers. Without establishing detailed requirements, the risk of project failure would be unacceptably high.

Requirement elicitation is an iterative activity and benefits from continuous communication and validation with the customer. No design can be completed before establishment of the System Requirements Documents (SRD) reflecting all relevant design inputs. In complex contests, with a number of stakeholders involved, requirements are not static and one reason for that is the continuous learning and better understanding of the design concept and its environment during design process. During the initial stages of conceptual design it may not be needed to establish all requirements; however, the necessary design criteria should be fixed before starting the related level of design. Moreover, constant changes occur to the systems during the early phase of conceptual stage.

Generally, in the development of complex mechanical systems the design process starts when the requirements are not completely defined from the beginning, but the information from the various partners working at the project will come in during the design activities.

In order to overcome these difficulties, in this paper we propose a design process for drafting solutions in an "incomplete requirements environment". In this kind of approach, the information will be completed during the design development. The process, named Iterative and Participative Axiomatic Design Process (IPADeP), is an iterative and incremental, participative process, requirements driven. It has been developed so as to minimize the risks related to the uncertainty and incompleteness of the requirements, and considering that the requirements will be refined and completed during the process. It was developed according to the design process roadmap proposed by Tate and Nordlund (1996), and it is based on the theory of Axiomatic product development lifecycle (APDL) [8] as regards the phases of requirements management and architectural development of conceptual solutions. Fuzzy AHP is used as a tool for decision-making. In order to test IPADeP methodology a case study concerning the design of fusion reactors (Tokamaks) was taken into account. Indeed the development of tokamak sub-systems has to take into account interface, structural and functional requirements and multiphysics issues that can be completely known only during the development of the process.

2 General background

A design process converts a need, a required functionality, into a product satisfying that need. Such a process is quite complex and requires designer's initiative, creativity and the availability of a wide range of skills, methodologies and experience in attaining a solution. Design proceeds from abstract and qualitative ideas to quantitative descriptions, and it is an iterative process by nature: new information is generated at each step and it is necessary to evaluate the results in terms of the preceding step [9]. Suh [10] sees design as a continuous interplay between the requirements (what) the designer wants to achieve and how the designer wants to achieve these requirements. Many engineers have been designing their products intuitively, based on their experience, involving much trial and error. This approach is very unsystematic (i.e., lacking of a definite plan) and overly time consuming. For this reason, experience gained from such practices cannot be easily reapplied to other similar issues. Although experience is important since it generates knowledge and information about practical design, experiential knowledge alone is not enough, as it is not always reliable, especially when the context of the application changes. Experience must be supported by systematic knowledge of design [10]. Design has always benefited from creativity, but this process must be augmented by systematically amplifying human capability to understand cognitive behaviour and by the development of scientific foundations for design methods [11]. In recent years, many researches have shown the importance of structured and scientifically based theories and methods for product (and process) design and development, in order to reduce development time, reduce product costs and increase value. As stated by Tate, Nordlund [12], an effective product development process, supported by scientifically validated design theories and tools, is becoming an increasingly useful asset in industry for reducing lead times and costs as well as for improving quality. Some design methodologies available in literature deal with most of PDL activities whereas other methodologies deal with the process of creating a solution to a stated need. According to [10] and [12] the design activities should start from the knowledge of the "customers' needs" and the definition of the requirements. Prior to proceed with the physical implementation, a complete, unambiguous, consistent, understandable, traceable, and modifiable set of requirements is needed [7]. However, in the early conceptual design stage the requirements for the project could be continuously provided from different actors involved in the design activities and completed during the design process.

Many types of systems have proven to be resistant to requirements determination. As a consequence, application of traditional management processes does not adequately assure operational effectiveness [13]. Several authors have dealt with requirements change and uncertainty in engineering [14], and according to [15] the later changes occur in the design process, the more people is affected. Moreover, the cost of implementing a change increases on average by a factor of 10 between each phase of the design process [16,17]. Companies usually integrate their customers in the design process and use instruments, such as Quality Function Deployment (QFD) [18], to build up a clear picture of their requirements to avoid later changes [19]. A the same time, companies apply the classical systems engineering V-model and test products virtually as soon as possible [15]. To generate Functional Requirements (FRs) and concepts at an abstract level QFD is an effective tool [20], but it can be difficult to select and specify design alternatives at a more detailed level [21]. On the other hand, to produce high-quality design alternatives at a parametric level Taguchi's robust design principles [22,23] have been widely used, but according to Thielman, Ge [21] is not clear how to apply Taguchi's principles when the generation of concepts from qualitative functionality descriptions is required. An approach based on Axiomatic Design (AD) simplifies the organization of complex design processes; it uses axioms to generate and evaluate design alternatives, combining a mapping and decomposition process (zigzagging) [10,11]. The application of the AD theory in a nuclear reactor system [21] demonstrated that this methodological approach represents a viable method for large-scale engineering systems development. AD deals with most of PDL activities, but it does not support the whole PDL [24]. To provide a systematic approach for PDL activities and management, and to ensure that all the activities in the PDL are aligned with the requirements at all times, Gumus et al. [8] proposed a new model (APDL) based on the systematic nature of AD. APDL is built as a V-shaped process to develop the initial design with a top-down approach, while producing and testing the product with a bottom-up approach [8]. APDL covers the whole product lifecycle including early factors that affect the entire cycle. APDL provides useful tools to address the problem of requirements traceability and design solutions creations but, in some aspects, it needs to be enhanced and better defined in order to provide a clear and systematic approach to design activity in the early conceptual design phase. The methodology here presented (IPADeP) aims to improve these aspects, proposing an incremental design process that deals with the change and completion of the requirements typical during the pre-conceptual and conceptual phases.

3 Materials and methods

The methodology described below has been developed in order to minimize the risks related to the uncertainty and incompleteness of the requirements, and considering that the requirements will be refined and completed during the process. The process, named Iterative and Participative AD Process (IPADeP), is an iterative, incremental, participative and requirements driven process. It was developed according to the design process roadmap proposed by Tate, Nordlund [12], and it is based on the theories of Axiomatic Design (AD) [10,11], Axiomatic Product Development Lifecycle (APDL) [25] and Fuzzy Analytic Hierarchy Process (AHP) [26,27] as a tool for decision-making.

3.1 Axiomatic Design

The AD method provides a systematic and logical method for deriving, documenting and optimizing designs. Furthermore it helps avoid traditional design-build-test-redesign cycles for design solution search and for determining the best design among those proposed. An extended explanation of the method is contained in [10] and [11]. There are four main items in AD: (I) domains, (II) hierarchies, (III) zigzagging and (IV) design axioms. Domains, which are four, are generalized as customer domain, functional domain, physical domain and the process domain. Design elements are associated with each domain. Elements within each domain are: Customer Needs (CNs); Functional Requirements (FRs); Design Parameters (DPs) and Process Variables (PVs). For each pair of adjacent domains, the domain on the left represents "what we want to achieve", while the domain on the right represents the design solution of "how we propose to achieve it". Therefore, the design process can be defined as mapping from the "what" domain to the "how" domain. FRs and DPs are developed to provide enough design information at the conceptual level and are decomposed until the design can be implemented. The decomposition is performed by zigzagging between the domains, starting from the "what" domain to the "how" domain. FRs and DPs hierarchies are established to represent the product design structure throughout the decomposition process. There are two axioms in AD, to support analysis, which can be stated as follows [11]:

- The independence axiom (first axiom): Maintain the independence of functional requirements. It means that each one of the FRs can be satisfied by its corresponding DP without affecting the other FRs;
- The information axiom (second axiom): Minimize the information content of the design. The purpose is to find the design with the highest probability of achieving the FRs.

During the mapping process (for example, mapping from FRs in the functional domain to DPs in the physical domain), the designer should take the correct design decisions using the independence axiom. When several designs that satisfy the independence axiom are available, the information axiom can be used to select the best design. Designers apply the independence axiom by using design matrixes that represent the mapping between the domains. The set of FRs that define the specific design goals constitutes a vector FRs in the functional domain. Similarly, the set of DPs in the physical domain that describe the design solution also constitutes a vector DPs. The relationship between the two vectors can be written as: $\{FR_s\} = [A]\{DP_s\}$, where $[A]$ is the design matrix that characterizes the nature of the mapping. Design matrixes and system architecture highlight the relationships between the FRs, DPs and Input Constraints (ICs); they can be used to evaluate the impact of proposed design changes as well as FR and constraint changes.

3.2 Axiomatic product development lifecycle

The APDL model utilizes the systematic nature of the AD method in order to provide a systematic approach for Product Development Lifecycle (PDL) activities and management, and provide an iterative and incremental way for a team of trans-disciplinary members to approach holistic product development. The APDL improves the AD in the area of domain entity description and management and takes the AD method one step further to support the test domain of the PDL [8].

One new domain and four new characteristic vectors are added to the existing AD domains and characteristic vectors. The methodology supports different development lifecycle activities, such as requirements and change management throughout the whole PDL. A characteristic vector for the System Components (SCs), that are the physical entities that provide the design solution stated in the DPs, is defined in the Physical Domain. The SCs hierarchy represents the physical architecture of the system. The Test Domain is added to the existing AD domains, and it contains the Component Test Cases (CTCs), that are used to verify the corresponding component that satisfies the allocated FRs, and the Functional Test Cases (FTCs).

The APDL model proposes a V-shaped process to develop the detail design with a top-down approach, and to produce and test the product with a bottom-up approach as shown in Fig. 1.

Once the FRs and the ICs are derived, they should be analysed to develop the system FRs, DPs, and SCs triplet that states the system objective, the proposed system design and the proposed SC. Then, the design decomposition and zigzagging process starts. Since the initial FRs can be at different levels of detail, they should be mapped to the FRs/DPs hierarchy during the decomposition process. Full integration of documentation as well as traceability throughout the development lifecycle should be provided. It is important to define standard templates for domain entities and for CNs, FRs, CTCs, and FTCs. The templates for documenting the domain entities and the mapping matrix have been presented by Gumus [25].

3.3 Iterative and participative axiomatic design process (IPADeP)

IPADeP is an iterative and incremental design process, participative and requirements driven. It provides a robust structure and systematic thinking to support design activities in the early conceptual design stage of large and complex systems. In this stage, even if the information are not yet completed, the requirements for the project will come in from the other actors involved in the project during the design activities (i.e. interface requirements). It is needed to start the design process in order to reduce lead-time basing on the assumptions that it is possible to do thanks to experiences in previous similar projects. IPADeP could be seen as an enhancement of the top-down side of the APDL V-model to better address the early conceptual design phase. It highlights the iterative nature of the design activities; for each level of decomposition iteration is performed, and from the second iteration also new information could come in the process from the stakeholders. The IPADeP flowchart is presented in Fig. 2.

The process starts with a first iteration that corresponds to levels 0-1 of decomposition. At this level the needs of the system are known but there is not yet a set of defined requirements. To start the process, brainstorming sessions between experts and stakeholders is performed in order to define few generic needs and then map these needs in the initial FRs and ICs. To document and trace the mapping process, according to the APDL method [8], we have used the Requirement Matrix and a Constraint Matrix templates by Gumus [25]. The output of this phase is defined in this work as FRs to maintain the definition used in AD. However, according with Kossiakoff et al. [28], we should not yet call this description a set of requirements, though they are certainly the forerunner of what will be defined as official require-

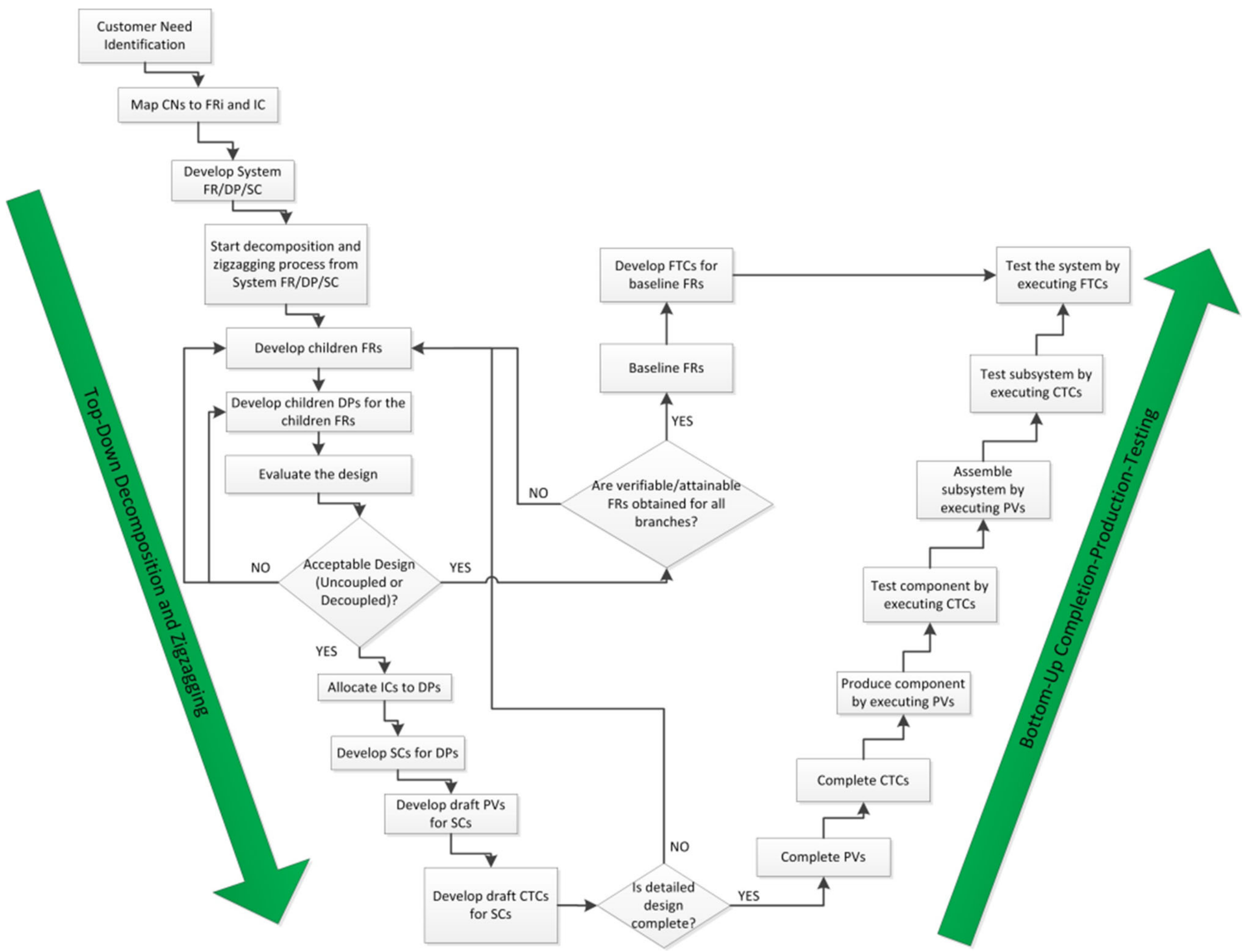

Fig. 1 V-model

ments. Once CNs are mapped to FRs and ICs, the top level design concept, System DP, and the top level physical system SC, should be proposed. From this triplet, FRs/DPs/SCs, the decomposition and zigzagging starts. Generally speaking, from the first brainstorming session enough information for a first level of decomposition is available. Several different DPs could satisfy a single FR and several SCs could be used to apply a DP. So several design solutions can be developed. Additionally, a design matrix to map between FR and DP is developed. Each design matrix can be diagonal (uncoupled design) or triangular (decoupled design) to satisfy the independence axiom. For each solution, a conceptual CAD model is also developed in order to show and clarify DPs and SCs. Concept solutions are designed in a CAD 3D software (CATIA V5 has been used in this work) using a top-down modelling approach in assembly environment. The comparison of concepts, their evaluation and the choice of the best solution, is performed using a multiple-criteria decision analysis (MCDA). In this work we propose the Fuzzy- Analytical Hierarchy Process (AHP) [26,27]. The AHP has been widely used by both researchers and practitioners in a MCDA where you have multi-criteria for decision making [29]. It has been proposed in literature as a methodology to large, dynamic and complex real-world MCDA problems[30,31]. Since decision maker's requirements may contain ambiguity and the human judgment on quality attributes may be imprecise [32], the crisp aspect of the conventional AHP seems inappropriate in depicting the uncertain nature of this decision phase. To consider uncertainties during the early stages of design and deal with the variables in verbal judgments, in this research AHP is used with a fuzzy approach, using triangular fuzzy numbers [33–35]. The process requires to consider in pairs first the evaluation criteria and then design solutions and ask expert(s) to respond, with a ratio, to the pair wise comparison of "which of Ai and Aj is more important, and by how much (how many times)?" The evaluation takes place by five main linguistic terms and the corresponding reciprocals (Table 1).

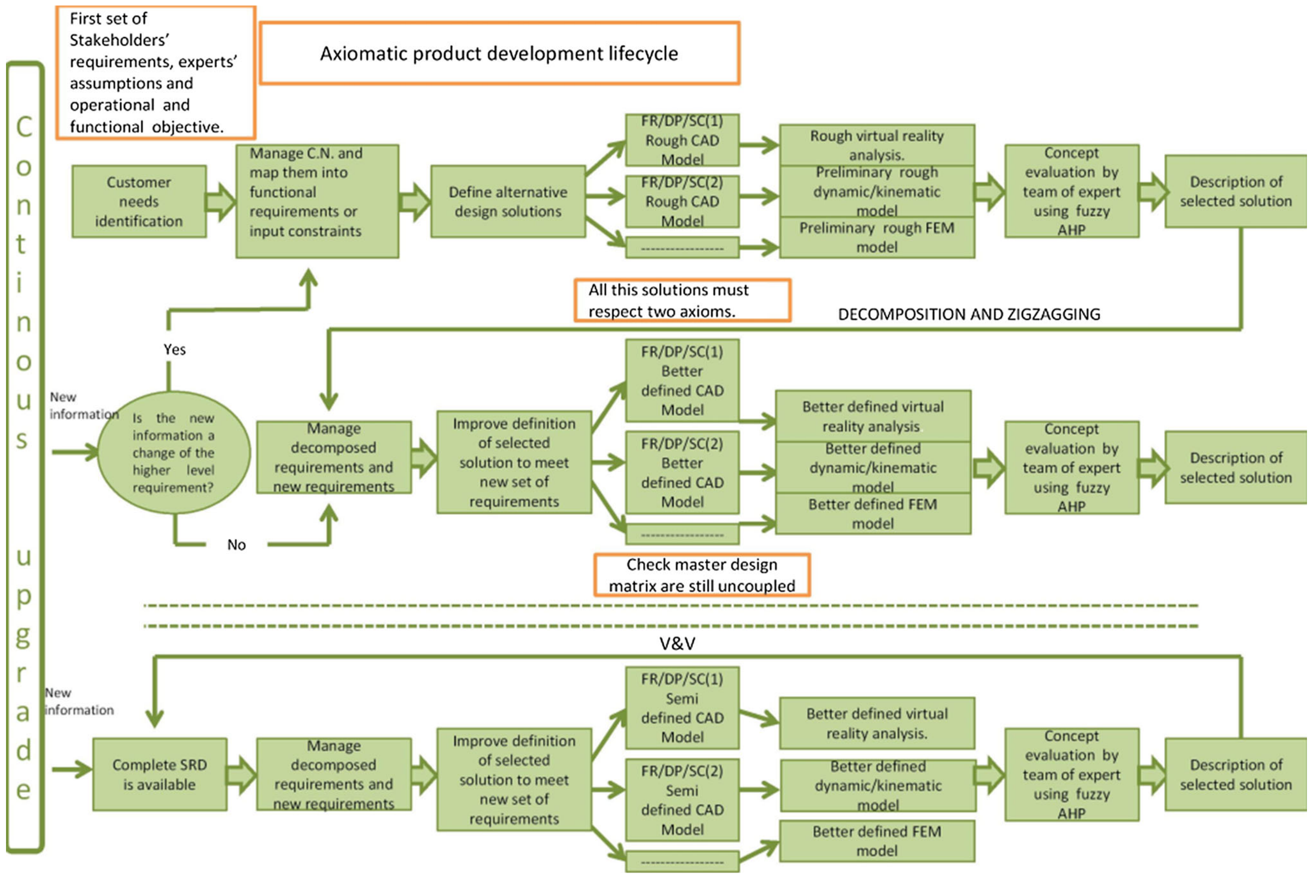

Fig. 2 IPADeP process

Table 1 Triangular fuzzy conversion scale

Linguistic scale for importance	Triangular fuzzy scale
Absolutely more important (AI)	(5/2, 3, 7/2)
Very strongly more important (VSMI)	(2, 5/2, 3)
Strongly more Important (SMI)	(3/2, 2, 5/2)
Weakly more important (WMI)	(1, 3/2, 2)
Equal important (EI)	(1/2, 1, 3/2)
Weakly less important (WLI)	(1/2, 2/3, 1)
Strongly less important (SLI)	(2/5, 1/2, 2/3)
Very strongly less important (VSLI)	(1/3, 2/5, 1/2)
Absolutely less important (ALI)	(2/7, 1/3, 2/5)

The team of experts involved in the evaluation process is different from the team that participated to the first brainstorming session in order to not be influenced from the design process. To provide to the evaluation team enough information to carry out the assessment using more objective data, solutions are presented in Virtual Reality environment and could be supported by preliminary and rough Finite Element Method (FEM) and/or kinematical/dynamical analyses. A FEM analyses can be a way to refine structural and material requirements, and provide a first idea about the necessary thickness and dimensions to withstand the high loads. Once the best solution is selected, the first iteration ends and a new iteration can start when there is enough information to decompose the solution (zigzagging) to the second level. Iterations could start also if new information arrives from other stakeholders, and requirements begin to be more defined. New information could be a change of a precedent assumption: in this case the process must restart, or could lead to a modification of FRs or ICs. Proceeding with the iterations the solution selected in the previous iteration is improved to meet the new requirements and constraints. One or more DPs are developed to meet the new FRs; so the master design matrix has to be used to check if the design still respect the independence axiom or the early design decision would be violated. If lower level DPs violate the higher level design, then three actions can be taken: 1) modify the lower level DPs; 2) impose constraints or specify conditions that prevents the DPs unwanted affects; 3) revise the higher level design matrix provided that the revised design matrix is still uncoupled or decoupled. During the decomposition and iteration, FRs are collected in a SRD. The iterations concerning the conceptual phase stop when this document is completed, all FRs and ICs are well defined and no further decomposition is needed. At this point all requirements are verifiable, attainable and approved by stakeholders and verification and validation activities can be performed to arrive at the first lifecycle decision gate: Conceptual Design Review.

4 Results of IPADeP application to a fusion engineering case study: conceptual design of the DEMO divertor-to-vacuum vessel locking system

Within the activities on fusion research, while ITER reactor is under construction, concept design activities have started for the DEMOnstration fusion power plant (DEMO), the tokamak that will demonstrate the feasibility of energy production from nuclear fusion and will mark the very first step of fusion power into the energy market by supplying electricity to the grid [36,37]. In this work IPADeP was applied to the initial phase of conceptual design activities for a tokamak subsystem, DEMO divertor-to-vacuum vessel locking system, to propose new innovative solutions that could overcome the difficulties in applying the ITER principles to DEMO [38,39]. Due to the lack and the uncertainly of the requirements in this early conceptual design stage, we covered the first interactions of the framework (decomposition level 0-1), and obtained an innovative concept to be developed in more details as information will be detailed.

4.1 Identification of customer needs

In this first step, meetings and discussions were carried out with stakeholders and experts 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 SRD, but the elicitation of a first set of requirements and experts' assumptions essentially based on the extrapolation of the studies on ITER Remote Handling (RH) process to DEMO (Table 2). Even if we would not yet call these descriptions a set of requirements, they are the forerunner of what will be defined as official requirements [28].

4.2 Mapping of functional requirements and input constraints

After the first needs and assumptions were gathered, according with APDL few generic CNs were extrapolated (level 0 of decomposition) and then they were mapped to Initial Functional Requirements (FRis) and Initial Input Constraints (ICis) (Table 3).

Table 4 shows the FRis and ICis mapped to CNs. The mapping was important to ensure requirements traceability during decomposition and zigzagging.

After CNs were mapped to the FRis and ICis, it was necessary to analyse the FRs to develop the system FR, DP, and SC

Table 2 Early assumptions, stakeholders' requirements

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
Locking System shall be compatible with remote installation and disassembly during divertor maintenance
Locking System shall be compatible with the transfer cask and RH geometries
It's preferable an ITER-like robotic manipulator for locking/unlocking operation
Inner locking shall be ITER-like nose-hook mechanism
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
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 Vertical Displacement Events (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 load cases (F = 0.7 MN * 1.4 = 0.98 MN)
The cassette shall be electrically connected to the vacuum vessel via the inner and outer locking system
Locking mechanism shall withstand operational radiation level
Material requirements: links connecting multilink attachments: INCONEL 718; divertor to vacuum vessel locking system: BRONZAL (Ni-Al bronze)

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	Maximize reactor availability using systems with short maintenance time and avoid unplanned stop

Table 4 Initial Functional Requirements and Initial Input Constraints

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

that states the system objective, the proposed system design, and the proposed system. Once the system FR/DP/SC triplet was developed, the decomposition and zigzagging process started.

4.3 Definition of alternative design solutions

As previously done with the elicitation of needs and assumptions, also in this stage brainstorming sessions were carried out. During each session, for each FR some alternative DPs and SCs were proposed by fusion experts. The documentation of the activities, the mapping, the design matrixes and decomposition are showed in Tables 5 and 6.

The next tables also reports the DP Type as classified by Gumus (2005): Type I-System level DP; Type II-Conceptual level DP; Type III-Subsystem level DP; Type IV-Attribute DP. The design matrix we adopted is illustrated in Equation 1.

$$\begin{Bmatrix} FR1.1 \\ FR1.2 \end{Bmatrix} = \begin{bmatrix} x & 0 \\ 0 & x \end{bmatrix} \begin{Bmatrix} DP1.1 \\ DP1.2 \end{Bmatrix} \quad (1)$$

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 allocation

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

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	III
		(b) Preload cassette taking advantage of the mass of cassette	

This decomposition level 0 was not enough detailed to define some SCs yet but it was possible to do that at the next level of decomposition. Tables 7, 8, 9 and 10 show the decomposition level 1 and the related SCs.

From the combinations between FRs and alternative DPs it was possible to obtain two new design matrices (Eqs. 2 and 3).

$$\begin{Bmatrix} FR1.1.1 \\ FR1.2.1 \\ FR1.2.2 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ X & 0 & X \end{bmatrix} \begin{Bmatrix} DP1.1.1(a) \\ DP1.2.1\,(a)\,(b) \\ DP1.2.2 \end{Bmatrix} \tag{2}$$

$$\begin{Bmatrix} FR1.1.1 \\ FR1.2.1 \\ FR1.2.2 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP1.1.1(b) \\ DP1.2.1\,(a)\,(b) \\ DP1.2.2 \end{Bmatrix} \tag{3}$$

Both showed an acceptable design with respect to the independence axiom, the first one being a decoupled design, the second one an uncoupled design. Analysing the combination of DPs and SCs proposed, different alternative ideas and solutions were suggested by experts involved in brainstorming sessions. Experts selected three concepts during brainstorming sessions as the most promising and feasible. We decided to create CAD models and perform FEM simula-

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:	Manufacturing and assembly processes
			Tool with spherical surface	
			Wedges arrangement	
			Hydraulic jack	
1.1.1 (b)	III	1.1.1 (b)	Gear arrangement	Manufacturing and assembly processes
			Cam arrangement	

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	IV
		(b) Insert tool able to take vertical forces	
1.2.2	Keep cassette in compressed position, avoid radial displacement	Insert component after preloading able to take radial loads	IV

Table 10 DP-SC-PV mapping: 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

tions for these concepts in order to have a greater perception of the solutions' feasibility.

4.4 Concept design in CAD software

The CAD model of the first solution generated during brainstorming sessions is shown in Fig. 3.

The concept idea was to preload the cassette pushing it with a spherical tool. The spherical surface on the tool has a minor radius than the spherical surface formed on the cassette, so that it is possible to provide the required preload and a relative displacement of 5 mm. All the degrees of freedom were constrained by socket engagements formed on cassette and supports.

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

For the third concept (Fig. 5) is exploited the mass of the divertor as well, using a "cam" arrangement instead of the gear. The principle of operation is the same as the previous solution.

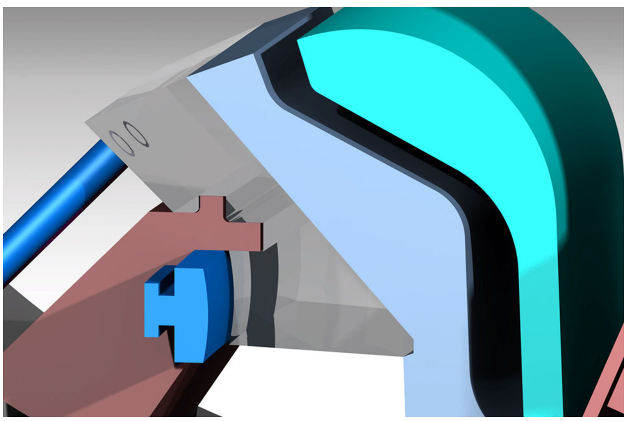

Fig. 3 Concept I

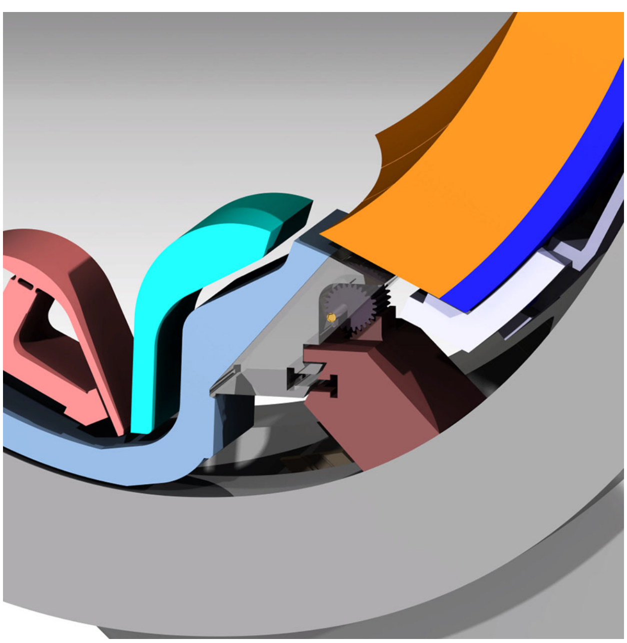

Fig. 4 Concept II

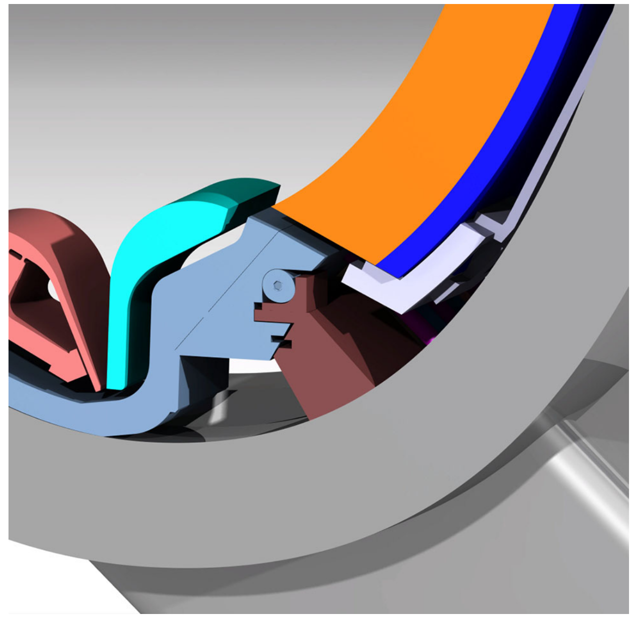

Fig. 5 Concept III

4.5 Preliminary FEM analyses

A FEM analysis was carried out on each solution as a support to the evaluation phase, to better understand the load distribution and, as a more objective way, to evaluate the structural robustness of the different solutions. FEM analyses were carried out using ANSYS Workbench, release 14. The models, designed in CATIA V5, were imported in the software and different contact areas were appropriately defined.

Since it was an high-level, rough analysis, the 3D model was considered in order to have an overview of the whole behaviour of the components, considering also that this type of analysis didn't required over-exploitation of resources.

The element used to mesh the solid model is the SOLID186, an higher order 3-D 20-node solid element that exhibits quadratic displacement behaviour. Contacts were simulated using elements TARGE170 and CONTA174.

Loads were extrapolated from ITER load cases [40]

Results of Von Mises stress are shown in Table 11; Fig. 6 shows the loads, the boundary constraint applied to the model and the graphical evaluation of the Von Mises stresses..

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

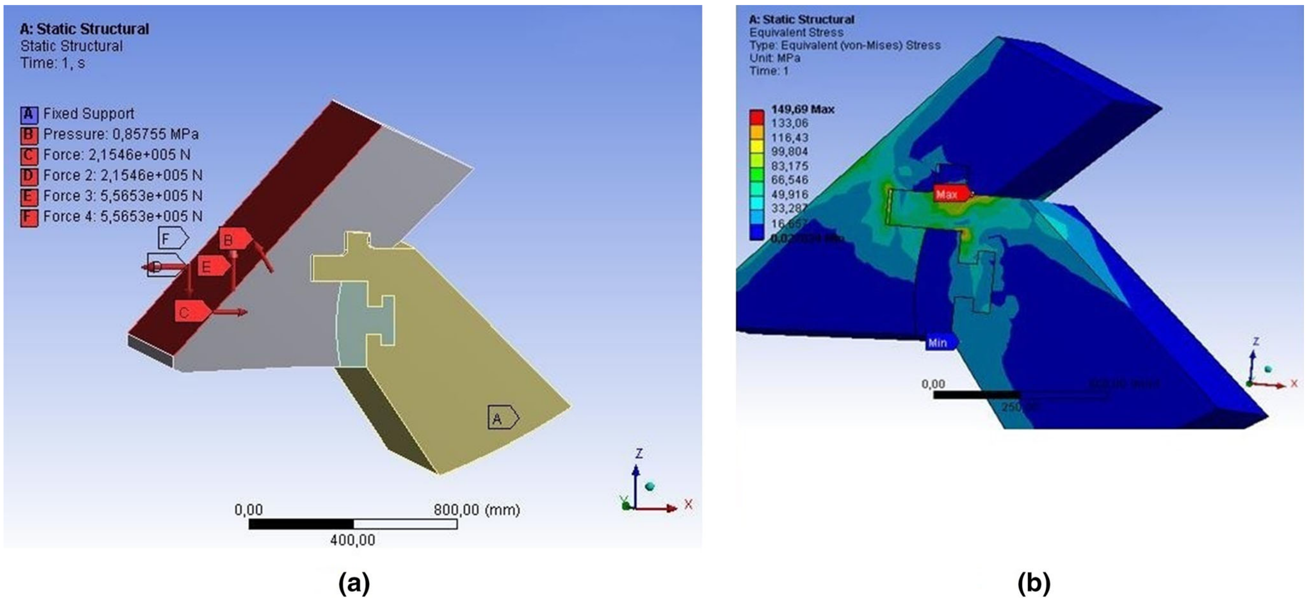

Fig. 6 (a) Loads and boundary conditions; (b)Equivalent Von-Mises stress (Concept I)

4.6 Multi-criteria analysis of concepts

Concept evaluation was carried out adopting the Fuzzy-AHP methodology, as previously described. Two different teams of experts were involved in the evaluation: the first was the "DTP-2" team at VTT Technical Research Centre of Finland, which was asked to fill the first section of the questionnaire. It covered the section about the "preference", in which the selected evaluation criteria were pair-wise compared. The chosen criteria are showed in Table 12.

Decision makers replied their preference about the criteria using fuzzy linguistic variables. After the transformation of the results obtained into triangular Fuzzy numbers, we calculated the average values and applied the extent analysis, obtaining the weight vector with respect to the decision criteria C1, C2, C3: $W = (0.3477; 0.343; 0.309)$. The pair-wise comparison among conceptual alternatives was carried out

Table 12 Evaluation criteria

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

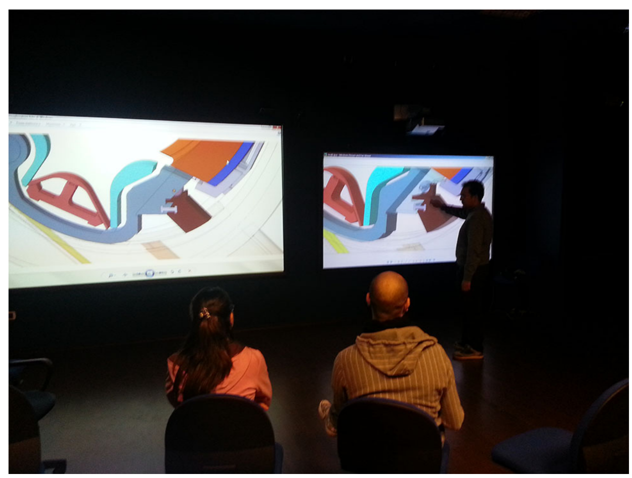

Fig. 7 Concepts' evaluation in IDEAinVR lab

in the the IDEAinVR Lab at CREATE/University of Naples "Federico II" - Department of Industrial Engineering [41], where a team of 25 engineers compared the alternatives with respect of each criteria using the fuzzy linguistic variables (Fig. 7).

Applying the extent analysis, the results of the questionnaire were used to estimate weights of each concept under

Table 13 Final results of Fuzzy-AHP evaluation

Criteria (weight)	Concept I	Concept II	Concept III
Simplicity (0.35)	0.623	0.225	0.151
Structural Robustness (0.34)	0.397	0.312	0.289
Ability to preload cassette (0.31)	0.163	0.398	0.437
FINAL SCORE	**0.404**	**0.309**	**0.287**

each criterion separately. Finally, a final score was obtained for each candidate (Table 13).
According to the scores, Concept I was the chosen alternative.

5 Discussion

PDL models and design methodologies should support requirements identification and design verification, starting from the very early stages. Traditionally, required input data for a design process are gathered from documents which can be incomplete and they do not capture the relationship between domain entities [8]. A suitable method to support design activities should first have an incremental and iterative nature that provides a continuous update and refinement of requirements and conceptual solutions. During all process activities, the experience of designers is fundamental, from the stage of "customer need identification" passing by the generation phase of the conceptual alternatives to the selection of the best alternative. Continuous design documentation throughout the process and dynamic requirements traceability play a central role providing the possibility to evaluate how each new requirement completed during the design activities affects higher-level decisions. Most of current PDL practices seem to be inappropriate to approach this problem. AD allows to efficiently deal with the high-level design, starting from few requirements with an high level of abstraction and proceeding step by step towards the detailing of the design. However it does not allow to address all issues related to the whole project development. APDL can provide useful tools to address the problem of requirements traceability and design solutions creations but, in some aspects, it needs to be enhanced to address the issues related the early conceptual design phase.

The process we developed in this study is based on the above methodologies, keeping the interest on the left side of the V-model (top-down approach) (Fig. 1). IPADeP can be seen as an enhancement of this phase with the scope to adapt it in an incomplete requirements environment. In order to overcome the problems derived from ambiguity and uncertainty of requirements in early conceptual design phase, all the process is based on the enhancement of human factor and the contribution of experts. Especially during the first iteration, brainstorming and problem solving sessions are performed, to define the first few fundamental requirements that the system must fulfil, and to develop alternative design solutions that meet the requirements but that could be also open towards new requests that may arise. Experts' opinion is required in the early phase of eliciting the first fundamentals customer needs, to propose conceptual solutions, and to evaluate the most suitable design against the first set of generic assumptions and FRs. Due to the high level of abstraction characterizing the early phase of conceptual design, several solutions could be equivalent about the information content, or solutions that are more adapted to future requirements may be rejected too early. Therefore it is preferable that a team of experts evaluate the solutions using a multi-criteria decision making tool, such as Fuzzy-AHP, which we have embedded in our method. To evaluate alternative concepts in terms of how they translate customer needs into the actual engineering characteristics of the product, it is essential that people involved is able to visualize the design to gain a comprehensive understanding of the product [42]. Functional behaviour of the product is difficulty provided using only physical prototypes or CAD models; a VR environment, combining VR-based interactions with functional behaviour simulation can satisfy such task [31,43,44]. In our methodology, CAD models and virtual simulation are used during each iteration of the process, with increasing level of definition, in order to provide an objective support to evaluation team.

6 Conclusions

In the present work we introduced a new iterative and participative methodological approach based on AD principles, IPADeP. This enhanced design process seems to be well suited for drafting solutions in an incomplete requirements environment, providing a systematic approach to deal with the early conceptual design stage of complex systems. We applied this methodological approach on the conceptual design stage in DEMO divertor-to-vacuum vessel locking system, where requirements are still uncertain and incomplete because of the early nature of design activities. IPADeP introduces a systematic method to achieve solutions in the conceptual design stage of complex assemblies, limiting the risks arising from the lack of requirements and proceeding iteratively, refining and completing the requirements at each iteration.

Finally, we can remark that early conceptual design based on IPADeP can operate as an interactive design technique [45, 46]: in fact it aims to support the "collective engineering", improving the collaboration among people and companies involved in the development process. IPADeP provides that concepts can be analysed using different simulations and the stakeholders are able to interact with the virtual prototype in order to evaluate and test it in a virtual environment. It allows design engineers to determine the best conceptual solution from two different perspectives: an objective perspective, based on the results of the analyses, and a subjective perspective, based on the experience of the evaluation team.

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