Iterative and Participative Axiomatic Design Process to Improve Conceptual Design of Large-Scale Engineering Systems

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Abstract. This research discusses the use of a systematic design method, the Iterative and Participative Axiomatic Design Process (IPADeP), for the early conceptual design stage of large-scale engineering systems. The involvement of multiple and competing requirements has imposed high challenges for achieving an affordable design of complex systems in a reasonable lead time. Systems Engineering (SE) focuses on how to design and manage complex systems over their life cycles. Both must begin by discovering the real problems that need to be resolved and identifying from the early stage of the design the main stakeholder requirements and customer needs. The Axiomatic Design (AD) methodology is widely recognized in the literature to efficiently support the design of complex systems from the early conceptual stage. IPADeP provides a systematic methodology for applying AD theory in the conceptual design of large-scale engineering systems, aiming to minimize the risks related to the uncertainty and incompleteness of requirements and to improve the collaboration of multidisciplinary design teams.

IPADeP has been adopted as design methodology in the pre-conceptual design stage of a subsystem of the DEMOnstration fusion power plant (DEMO): the divertor cassette body-to-vacuum vessel locking system. In this paper improvements in IPADeP are presented and its validity is discussed by presenting the application to the divertor system design.

Keywords: Axiomatic Design · Systems Engineering · Design methods · Tokamak design

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1 Introduction

The large and complex engineering system design is involving increasingly geographically dispersed and multi-disciplinary working groups, dealing with multiple and competing design objectives, so more and more attention is paid to global cooperation, especially during the conceptual design stage. Currently, most design groups use local and segmented approaches, which cannot provide a shared evaluation of competing design alternatives among the involved stakeholders and partners [1]. Moreover, due to the long lead time of the implementation process for the large system design, the implementation tasks are usually determined based upon incomplete design information [2]. Consequently, the information and changes coming in the project during the design process usually require several iterations to search for a proper result, having significant impact on the cost, quality and schedule of projects.

In this context, a design methodology would provide a systematic approach to design from the early conceptual design stage, aiming to avoid traditional design-build-test-redesign cycles and to allow for the evaluation of the design alternatives on a common basis with different stakeholders and across different design phases. The early conceptual design stage, dealing with an high level of abstraction, have recently attracted increasing attention from the academia [3, 4]. The conceptual design stage is responsible for more than 75% of the cost of a product and it is the top cause of troubled projects since the requirements sometimes are unclear, imprecise, with lack of agreement and priority [5].

The traditional practice of systems engineering management [6] 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 Systems Engineering principles, a systematic and efficient design methodology is needed to deal with the early conceptual design stage of large and complex system. In this methodology, the design should start from abstract ideas and proceed to detailed design with an incremental process. It should ensure the traceability and documentation of the design and should provide an efficient method to evaluate competing conceptual design alternatives.

Several design methods and theories are available in literature, some focusing on concept generation and selection, others helping the requirement management and quality development, others highlighting the steps to be performed during the design development.

The Axiomatic Design (AD) methodology [7] is recognized to provide designers with a tool to structure their thought processes in the early design stage and for optimization later in the design process. AD provides design parameters specification from the higher qualitative level to the lower quantitative level. Moreover, the design matrix and decomposition process facilitate the design documentation, the information traceability, the identification of changes impact and the achievement of multiple competing design objective.

According with these considerations in [8] we proposed an axiomatic design methodology, the Iterative and Participative Axiomatic Design Process (IPADeP), which provides a systematic approach to the conceptual design activities, based on the theory of AD. 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. The conceptual stage is characterized by fuzzy and incomplete information, making the design process quite difficult and challenging. For this, 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).

This paper presents recent improvement implemented in the IPADeP process, mainly focusing on the requirements engineering aspects and on the management of the design changes. A case study addressing the early conceptual design stage of tokamak fusion reactor components is discussed to highlight the benefits of the IPADeP application.

2 An Innovative AD Process: IPADeP

2.1 Motivation

Systems engineering theory [6] defines six life cycle stages, with predefined levels of developemnt, in order to establish a framework for meeting the stakeholders' needs in an orderly and efficient manner.

The product development through the six stages is supported by the technical processes, which are usually represented by the V model, which highlights the need to define verification plans during requirements development, the need for continuous validation with the customers and the importance of continuous risk and opportunity assessment [9]. The assumption is that the elicited requirements provide all necessary information needed to move forward. However, this does not usually happen in real-world design of large-scale systems, in particular as regards the interfaced sub-system, the development of which proceeds in parallel and involves the continuous updating and refinement of the technical interface requirements.

The main motivation that leads to the development of IPADeP comes from the finding that, as discussed, in many projects regarding large and complex systems, there is a need to have a process that provides a robust structure and systematic thinking to support design activities in the early conceptual design stage. The necessity of reducing lead-time commonly imposes to start design process at a stage suffering from lack of information and incomplete set of requirements which is generally integrated during the project from the other actors involved in the design activities (i.e. interface requirements).

A suitable method to support the design activities in this environment must first have an incremental and iterative nature that provides for continuous updating and refinement of requirements and the continuous improvement of the conceptual solution. During all process activities the experience of designers is fundamental, from the "Customer need identification" (especially in the first iteration of the process) to the generation of the conceptual alternatives and the selection of 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.

The AD and the APDL methodologies address the problem of requirements traceability and generating design solutions but, in some aspects, they miss a clear and systematic approach to design activity in the early conceptual design phase. Moreover, the new methodology has to provide a quantitative technique able to deal with the selection of the best conceptual solution considering the “fuzzy” nature of the information at this stage.

First applications of IPADeP, presented in [10] and [11] suggest some aspects to be better evaluated and discussed. A main point is that during the design process of a large-scale system, the first source of complexity lies in the identification customer and stakeholders and their distinction. For a technical complex system the customers define, through statements, the system functions and its expected behavior, leading to the main design drivers. In parallel, there are several stakeholders (technical partners, regulators, etc.) which provides constraints, interfaces and functional requirements.

Both customer needs and stakeholders needs are better being captured from the beginning or as soon as they become available during the design process, since (i) they represent the initial set of guidelines for the design of the system structure and the development of alternatives, and (ii) the selection of a balanced solution depends on how they are clear and complete. Furthermore, depending on the nature of the system being design, the relative contribution of these different sources of needs may vary depending on the level of complexity and/or technical readiness of the system as well as the applicable regulation, etc.

For instance, the initial design phase for systems that provide for a broader range of users, e.g. a cruise ship, is mainly driven by the customers’ needs and expectations and it is devoted to the elicitation and focalization of such needs.

Alternatively, as for the chosen study on tokamak fusion reactor discussed in Sect. 3, design activities are mainly driven by the technical requirements coming from the stakeholder needs. By the way, in both cases, the transformation of the needs into a set of clear and technically usable requirements is needed to proceed with the design development.

Another main characteristic of complex systems is that a prospective system element may itself need to be considered as a system (that in turn is comprised of system elements) before a complete set of system elements can be defined with confidence (ISO/IEC15288, 2008), as depicted in Fig. 1. As the system is decomposed, the requirements are also decomposed into more specific requirements that are allocated to the system components.

This implies the design process to be hierarchically structured and it allows for the easy understanding of the cross impact between system elements, sub-systems and system of interest. In other words, there is the need for a tool to check how the requirements and constraints on each element hierarchically impact on the system structure.

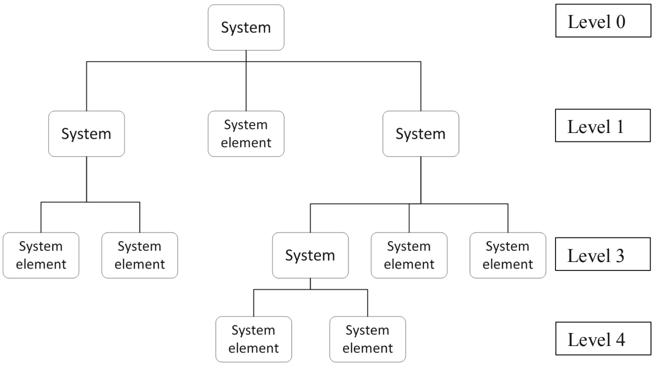

Fig. 1. System structure

2.2 Iterative and Participative Axiomatic Design Process

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 [12] 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. The process highlights the iterative nature of the design activities; for each level of decomposition iteration is performed, and from the 2nd iteration also new information could come in the process from the stakeholders. IPADeP aims to drive the conceptual design activities avoiding traditional design-build-test-redesign cycle. It integrates brainstorming sessions, MCDM techniques and the AD method, taking advantages of its systematic and logic approach for design derivation, documentation and optimization. Furthermore, it proposes the use of CAD and simulation software from the early stage to improve idea generation and communication among stakeholders and takes advantages of documentation templates and of the Master design matrix to document the design and evaluate the impact of requirement changes during the project.

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 smooth evolution from uncertain information during the early stages towards more detailed solutions emerging across subsequent design iterations is dealt with using Fuzzy- AHP during decision making steps. Compared to the previous version [8] the process presented in this paper has been improved in particular as regards the requirements definition and change management. Furthermore in this work it is highlighted the hierachical structure of the design process as a main point to avoid re-design cycles and minimize the impact of requirements changes during the design activties. As discussed above, during the design process of a large-scale complex system the informations are continuously updated and improved and new requirements needs to be managed and integrated (e.g. interface requirements). Differing from the requirements coming from the selection of a higher-level concept solution, these requirements are not well handled by AD, and require the looping provided by IPADeP. The process is exemplified in following sub-sections.

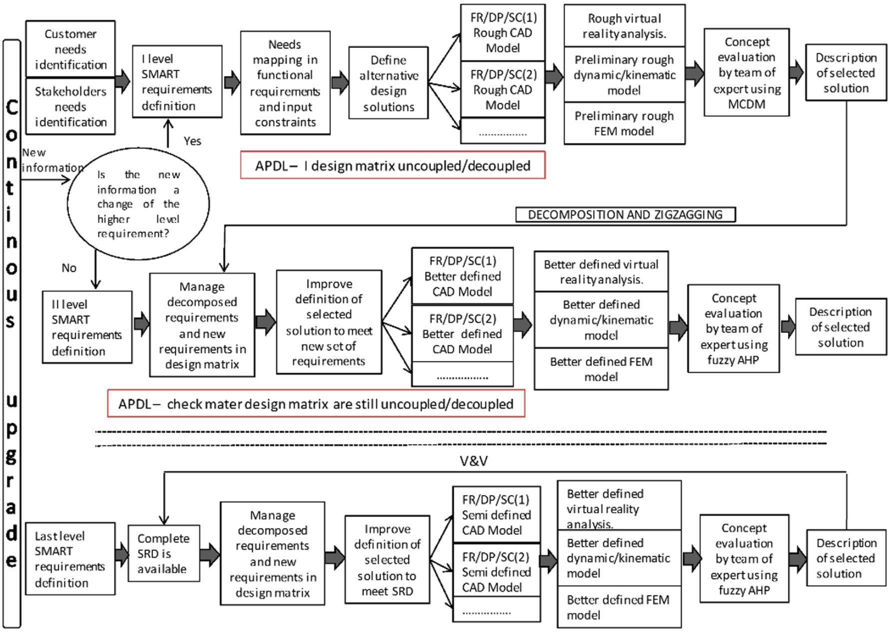

Fig. 2. New IPADeP flowchart. (FR: Functional requirements, DP: Design Parameters, SC: System Components, MCDM: Multi-criteria Decision Making, SRD: System requirements document, AHP: Analytic Hierarchy Process)

2.2.1 First Iteration

The process starts with first iteration corresponding to the first level of decomposition. Each iteration of the process can be divided in three macro area:

(1) Requirements identification and analysis

At this level the systems functions are known but there is not yet a set of defined requirements. To start the process, a brainstorming session between sector experts, customers and stakeholders is performed in order to collect few generic high-level needs. At this point, to start with design activities the transformation of the needs into a set of technically usable functional requirements is needed. These requirements should be also SMART requirements, where SMART is a mnemonic acronym giving criteria to write good requirements. Letters S and M usually indicate specific and measurable respectively, while the letters A, R and T indicate respectively achievable, relevant and traceable.

The Customer and stakeholders' needs are then mapped in the initial functional requirements (FRs) and input constraints (ICs). This mapping process is done according to the APDL method and using Requirement Matrix and Constraint Matrix to document and trace the process.

The mapping between the CNs and the initial FRs and ICs is captured by the equations:

$$\{CN\} = [R]\{FR\} \tag{1}$$

$$\{CN\} = [C]\{IC\} \tag{2}$$

(2) Design solutions development

Once CNs are mapped to FRs and ICs, the top-level design parameter (DP) and the top-level physical system components (SC), are proposed in order to start the decomposition and zigzagging process. 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 should be developed and modelled in a CAD system to show and clarify DPs and SCs.

For each solution, templates for design activities documentation are used and a design matrix to map FRs onto DPs is developed. For each solution the design matrix has to be diagonal (uncoupled design) or triangular (decoupled design) to satisfy the Independence Axiom (Eqs. (3) and (4)). Also, system Structure matrix to DP-SC mapping is developed.

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \end{Bmatrix} \tag{3}$$

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ X & 0 & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \end{Bmatrix} \tag{4}$$

(3) Concepts evaluation and first level solution selection

The comparison of concepts, their evaluation and the choice of the best solution is performed using a multiple-criteria decision analysis (MCDA). 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 [13]. During this phase, erroneous solutions need to be minimized, which means that several facets of the problem have to be considered concurrently. Analytic Hierarchy Process (AHP) has been proposed in literature as a methodology to large, dynamic and complex real-world MCDA problems [14]. Since decision maker's requirements may contain ambiguity and the human judgment on quality attributes may be imprecise [15], 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 [16].

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. The application of the fuzzy-AHP in the concept evaluations stage of the IPADeP process is detailed discussed in [8] and [11].

2.2.2 Subsequent Iterations

Proceeding with the iterations, when enough information are available to decompose the solution to the subsequent level, according to zigzagging and decomposition, the solution selected in the previous iteration is improved to meet the new requirements and constraints. One of the main improvements of IPADeP with respect to classical AD application is that a new iteration could start also if new information is made available from other stakeholders, and the needs are accordingly updated. New information could invalidate a precedent assumption, therefore requiring the process to restart, or can introduce a new FR or IC. In the latter case, one or more DP must be developed to meet the new FRs; so the master design matrix (Table 1) is exploited to check whether the design still respects the independence axiom, or the early design decision is violated.

Table 1. Master design matrix

	DP1.1	**DP1.2**	**DP2.1**	**DP2.2**	**DP2.3**	**DP3**
FR1.1	X	O	O	O	O	O
FR1.2	X	X	O	O	O	O
FR2.1	O	X	X	O	O	O
FR2.2	O	X	O	X	O	O
FR3.1	O	X	O	O	O	X

New FRs

If lower levels DPs violate the higher-level design, the design issue can be addressed by modifying the lower level DPs, revising the higher-level design matrix or imposing constraints to prevent DPs unwanted effects.

During the decomposition and iterations, the SMART requirements are collected in a System Requirements Document (SRD). The iterations concerning the conceptual phase stop when this document is completed, all functional requirements and input constraints are well defined and no further decomposition is needed. At this point all requirements are verifiable, attainable and approved by stakeholders, so Verification and Validation activities can be performed to arrive at the first lifecycle decision gate: Conceptual Design Review.

3 Design Progress of DEMO Divertor Cassette to Vacuum Vessel Locking System

IPADeP was used to deal with the conceptual design of the DEMO fusion reactor mechanical components. In particular, the driving case study was focused on the design of an internal reactor component: the divertor cassette body 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. 4), withstanding the electromagnetic, seismic, thermal loads avoiding vibrations.

First design iterations were performed and presented by authors in [10] and [11].

According to IPADeP, the design process started from the main high-level customer needs and stakeholder needs, collected and document in the traceability tables as shown in Table 2. The needs have been than translated in SMART requirements for the first design iteration. Keeping good documentation and traceability, this kind of approach supports the requirements elicitation and the change management, avoiding redesign cycle. The complete decomposition levels 1 and 2, including system components, CAD models, FEM analysis and design matrices are reported in [10] and [11]. Following the IPADeP flowchart (Fig. 2), Sect. 3.1 reports the third level design iteration developed because of significant changes occurred in the high-level requirements.

3.1 Third Iteration

The third iteration of the locking system conceptual design started from three main updates in the available information, regarding the configuration model and a required function of the locking system:

- Divertor locking system shall be compatible with the divertor configuration model 2017. Differences with divertor 2014 are shown in Fig. 3.
- The locking system shall ensure the electrical connection to the vessel and shall be able to carry the maximum current during plasma disruption
- Avoid sliding surfaces in vacuum environment

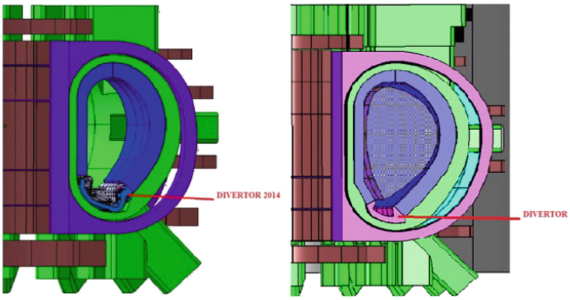

Fig. 3. New divertor configuration model

The first information represents a higher-level change. From the mapping tables it was easy to check that this change affects a higher-level input constraint and all the design parameters developed during the first iteration can be adopted also with the new constraint. This implies that, since according to IPADeP the project started from a high level of abstraction, all the second level DPs can be adapted to respect the new geometrical boundaries. The second information adds new SNs (SN3 and SN4) as shown in Table 2. The updates FRs and ICs are reported in Table 3.

Table 2. Third iteration: Customer and stakeholder needs

CN ID	Statement
CN1	Lock divertor in place after placement operations, avoid displacement in any load conditions
CN2	Maximize reactor availability using systems with short maintenance time and avoid unplanned stop
SN ID	Statement
SN1	Avoid “shaking” due to sudden change of magnetic field
SN2	*Accommodate distortions*
SN3	*Provide electrical connection between divertor cassette and Vacuum Vessel during operations*
SN4	*Avoid sliding surfaces*

Table 3. Third iteration: FRs and ICs

FRi ID	FRi description	CN/SN					
		CN1	CN2	SN1	SN2	SN3	SN4
FRil	Remove clearances to avoid vibrations – *clearances of maximum 5 mm*	0	X	0	0	X	0
FRi2	Provide an outer locking system able to take force in any direction – *ITER-like loads to be considered*	X	0	0	0	X	0
FRi3	*Provide a system to accommodate thermal distortion for a total displacement of 10 mm*	*0*	*0*	*0*	*X*	*0*	*X*
Fri4	*Provide a system to ensure electrical connection during sudden change of magnetic field*	*0*	*X*	*0*	*X*	*X*	*0*
ICi ID	IC description						
ICi1.1	Locking System shall be compatible with remote installation and disassembly during divertor maintenance – *take as reference ITER RH tools*	X	X	X	0	0	X
ICi1.2	*As simple as possible* mechanism to lock and preload in order to reduce operational time	X	X	X	0	0	X
ICi1.3	Locking System shall be the same for all standard cassette (left and right)	X	X	X	X	0	0
ICi1.4	Structural robust looking system – *withstand ITER-like extraordinary events*	X	X	X	X	0	0
ICi1.5	*Geometry and interface consistent with Divertor CAD model 20I5*	*X*	*X*	*X*	*X*	*0*	*X*
ICi1.6	*Deadweight 4 ton*	*X*	*X*	*0*	*0*	*0*	*0*
ICi1.7	*Avoid sliding surfaces*	*0*	*0*	*0*	*X*	*0*	*X*

The DP meeting these functional requirements added in the third iteration are reported in Table 4. They has to be considered as added to the ones reported in the first and second iteration tables, available in [10] and [11].

Table 4. Third iteration: FRs and DPs

Level	ID	FR	DP
0	1.4	Ensure electrical connection between cassette and vacuum vessel	Avoid relative displacement between cassette and Vacuum Vessel under ITER-like load conditions
I	1.4.1	Avoid relative displacement between cassette and vessel under ITER-like load conditions	(a) Preload cassette to ensure the connection (b) Provide electrical strap between cassette and vacuum vessel (c) Provide elastic elements in the outboard area to ensure connection in any condition
II	1.4.1.1	(a) Insert tool to preload cassette (b) Provide electrical strap (c) Provide elastic elements	(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) Bolted electrical strap (III) Disc spring in the outboard area to preload a Stainless Steel component against the Vacuum Vessel

The new DPs have been added to the master design matrix for the option selected during second iteration. As example, one of the master design matrices updated with the new DPs is reported (5). It shows that the design solution is still uncoupled.

$$\left\{\begin{matrix} FR1.1.1 \\ FR1.2.1 \\ FR1.2.2 \\ FR1.3.1 \\ FR1.4.1 \end{matrix}\right\} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ X & 0 & X & 0 \\ 0 & 0 & 0 & X \\ X & 0 & X & X \end{bmatrix} \left\{\begin{matrix} DP1.1.1(a) \\ DP1.2.1(a)(b) \\ DP1.2.2 \\ DP1.3.1(a)(b) \\ DP1.4.1(a)(b) \end{matrix}\right\} \tag{5}$$

Basing on the new DPs and ICs, the design of higher-level solutions has been improved and other solutions have been proposed, given the new geometric constraints, the lower weight and the new FR4 and IC7. The solutions are showed in Fig. 4. Also, in this case the application of IPADeP allowed for avoiding re-design cycle thanks to the hierarchical development from higher level solution towards more detailed solutions and the use of traceability matrix to easily check the FRs affected from each DPs modified.

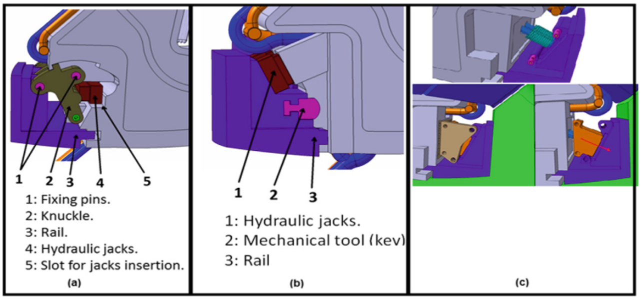

Fig. 4. Third iteration design solutions

According to IPADeP, as for second iteration, solutions were compared by means of Fuzzy-AHP, leading at the preferred solution, identified in the "Knuckle system" (Fig. 4a) emerging as an improvement of the second level solution considering the new geometric constraints.

4 Conclusions

The work presents IPADeP improvements in requirements engineering aspects and provides systematic procedure for the definition of SMART requirements. IPADeP seems to be well suited for drafting conceptual solution of large and complex systems. Basing on the AD theory, it provides a systematic approach to address the early stage of the design, dealing with the uncertainty of the available information. Moreover, proceeding iteratively layer by layer it allows an easy integration of the new requirements and subsequent design parameters, avoiding redesign cycles. The main characteristics of the new IPADeP version here presented can be summarized in: (i) IPADeP supports the management of new information coming late in the design process due to parallel development of high technical complex sub-systems; (ii) using APDL templates and design matrix it aims to provide good traceability of the design activities, improve design documentation and communication; (iii) the definition of SMART requirements allows for improved requirements statement. The writing of "good" requirements from the beginning is fundamental to correctly evaluate the alternative solutions and avoid re-design cycles; (iv) the design process is hierarchically structured and this allow for the integration of sub-systems and system elements.

IPADeP has been adopted for 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.

In this work the design progress of locking system is re-discussed according to the improvements in IPADeP and the second and third design iterations are presented. The improvements in the method allowed for better definition of requirements and design solutions and for a more robust decision-making stage. New solutions for divertor cassette body-to-vacuum vessel locking system were proposed and pairwise compared, leading to the selection of a reference solution for the third iteration. Starting from these results a new iteration for the divertor locking system will be performed when new information and requirements will be available. Moreover, further studies about the IPADeP application in design of large-scale system, technically challenging and involving a wide range of physics (e.g. new aerospace systems), shall be performed, in order to enhance its characteristics and validity.

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