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"*IPADeP: A Systems Engineering process for conceptual design of Tokamak sub-systems*"

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ABSTRACT

Engineering development of large-scale engineering systems is becoming increasingly knowledge-intensive and collaborative. The involvement of multiple, competing functionality requirements and lots of resources has imposed high expectations, and at the same time challenges, for achieving reliable, affordable design. In this contest, concept design stage results a complex and iterative process in which design tasks are highly interdependent. While design freedom is at its maximum in early design stage, product knowledge is only partially known initially and is changing over time.

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. Systems Engineering 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) has demonstrated its strength in various type of systems design. IPADeP provides a systematic methodology for applying AD theory in the conceptual design of large-scale engineering systems.

The IPADeP process is an iterative and incremental, participative process, requirements driven. It aims to provide a systematic process to face the conceptual design activities minimizing the risk related to the uncertainty and incompleteness of the requirements and to improve the collaboration of multi-disciplinary design teams.

IPADeP has been developed within the pre-conceptual design activities of the DEMOnstration fusion power plant sub-systems. Accordingly, the second main aim of this dissertation is to discuss and demonstrate the advantages in using IPADeP in large-scale engineering system, in particular for the applications concerning the design of fusion tokamak reactors. Indeed the development of tokamak sub-systems has to take into account interface, structural, functional requirements and multi-physics issues that can be completely known only during the development of the process.

The conceptual design o DEMO divertor fixation system has been used in this research to prove the general efficacy of the methodological instruments considered in dealing systematically with the conceptual design stage of systems characterized by high levels of complexity and poor knowledge of the technologies.

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CONTENTS

1 INTRODUCTION 1

1.1 OBJECTIVES AND CONTRIBUTION......5

2 BACKGROUND......6

2.1 SYSTEMS ENGINEERING......6

2.1.1 Life cycle stages......8

2.1.2 Conceptual Design Stage 12

2.1.3 Technical processes 13

2.2 REQUIREMENTS MANAGEMENT 17

2.3 CHANGE MANAGEMENT 20

2.4 SYSTEMS ENGINEERING TOOLS......21

2.4.1 System Modelling & Requirement Identification......21

2.4.2 Design methods for concept development......24

2.4.2.1 Axiomatic design......28

2.4.2.2 Axiomatic Product Development Lifecycle 31

2.4.3 Decision Analysis......32

2.5 SUMMARY......35

3 METHODOLOGY......37

3.1 ITERATIVE AND PARTICIPATIVE AXIOMATIC DESIGN PROCESS......37

3.1.1 Motivations......37

3.1.2 Iterative and Participative Axiomatic Design Process 40

3.1.2.1 First iteration......43

3.1.2.2 Subsequent iterations......58

4 IPADEP APPLICATION TO TOKAMAK SUB-SYSTEMS......60

4.1 OVERVIEW ON THE DEMONSTRATION FUSION POWER REACTOR DEMO 60

4.2 CONFIGURATION MANAGEMENT OF THE EU DEMO CONCEPTUAL DESIGN DATA 64

4.2.1 Selecting the product data management tool 64

4.2.2 Configuration management philosophy for DEMO CAD design data 67

4.2.3 Enablers of the configuration management of the design data 70

4.3 CONCEPT DESIGN OF DEMO DIVERTOR 72

4.3.1 Customer needs and stakeholders needs identification 72

4.3.2 First level SMART requirements definition 78

4.3.3 Alternative design solution definition 80

4.3.3.1 CAD design in CATIA V5 84

4.3.4 Preliminary verification 87

4.3.5 Concept evaluation using Fuzzy-AHP 90

4.3.6 Description of selected solution 94

4.4 SECOND ITERATION 94

4.5 THIRD ITERATION 103

4.6 DIVERTOR CASSETTE DEVELOPMENT. 111

4.6.1 PFCs cooling integration on cassette body 112

4.6.1.1 Cooling layout option 1 112

4.6.1.2 Cooling layout option 2 113

4.6.1.3 Cooling layout option 3 113

4.6.2 DEMO divertor cassette body conceptual design 114

4.7 CHOICE OF A LOW OPERATING TEMPERATURE FOR THE DEMO EUROFER97 DIVERTOR CASSETTE .. 116

5 CONCLUSIONS 124

6 REFERENCES 126

1 INTRODUCTION

The development of new products has been the focus of any economic system, since the beginning of civilization. As society progressed technically, so did the complexity of the products created. The involvement of multiple and competing requirements has imposed high challenges for achieving an affordable design of complex systems in a reasonable lead time. Actually, due to the rapid technical evolution and global competitive environment, 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 (Li and Qiu 2006).

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 (Kim and Cochran 2000).

Most design groups use local and segmented approaches that cannot provide a common understanding of the design and customer needs, as well as a shared evaluation of competing design alternatives among the involved stakeholders and partners (Thielman and Ge 2006). Moreover, due to the long lead time of the implementation process for the large systems design, the implementation tasks are usually determined based upon incomplete design information (Xue *et al.* 2006). 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.

Early conceptual design stage, dealing with an high level of abstraction, is the most crucial task in an engineering product development lifecycle (Wang *et al.* 2002). Recent researches have shown that the top cause of troubled projects regards the early design stage and this is related to the requirements that sometimes are unclear, with lack of agreement and/or priority, contradictory, ambiguous and imprecise (PM Solutions 2011). These situations are common at the beginning of the design process (especially before detailed design as defined by Pahl and Beitz (Pahl *et al.* 2007)), due to numerous experts involved in integrated and collaborative design (Legardeur *et al.* 2010).

The current Product Development Lifecycle (PDL) approaches lack a formal framework supporting this stage and they are usually not based on scientifically validated design theories and tools. 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 (Fredriksson 1994).

When needs are identified, organizations sometimes struggle with setting clear objectives and sharing the project's intent throughout the organization.

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 (Wang *et al.* 1994). 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 lack of a closely coordinated design can lead to integration issues, so the relationships between requirements, functions and elements should be efficiently communicated to develop effective concepts.

The impact of making design 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 (Figure 1) (IMTI 2000) . 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.

This commitment to life-cycle costs and loss of design freedom make the early stage of concept design among the most important of a program (Wheelwright and Clark 1992) . Hence, the necessity of efficient processes for defining large and complex systems.

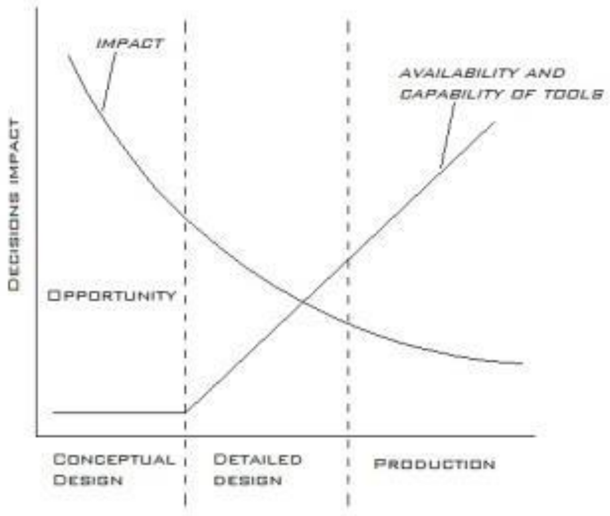


Figure 1 Design maturity vs opportunity

With the introduction of the international standard ISO/IEC 15288 in 2002 (Arnold 2002), Systems Engineering discipline was formally recognized as the preferred mechanism for managing engineering activities in highly integrated environments. However, especially when dealing with innovative product development, organizations need clear framework and tools to systematically deal with the concept design, the documentation and traceability of design information and to quickly explore many concepts and easily determine those most likely to succeed.

Within the context of ISO/IEC 15288:2008 and INCOSE Systems engineering handbook (Haskins *et al.* 2006), 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 contexts, 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.

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.

This even greater occurs when the systems under design is characterized by a high level of unknown technology to be developed.

The need of this research came out from the necessity to have a conceptual design framework to deal with the development of an innovative fusion reactor, the tokamak machine DEMOnstration Fusion power Plant (DEMO) (Maisonnier *et al.* 2006), which project is actually characterized by research activities in innovative technologies and materials and integration of multi-physics analyses. Basing on this experience, this research propose a design process framework, named Iterative and Participative Axiomatic Design Process (IPADeP), which aims to improve the use of different systems engineering tools and methodology to deal with the main issues characterizing the conceptual design stage of large/complex systems. It was developed according to the design process roadmap proposed by Tate and Nordlund (Tate and Nordlund 1996), and it is based on the theory of Axiomatic Design (AD) (Suh 2001) and Axiomatic Product Development Lifecycle (APDL) (Gumus *et al.* 2008) as regards the phases of requirements management and architectural development of conceptual solutions. Fuzzy- Analytic Hierarchy Process (Ayağ and Özdemir 2006) is used as tool for decision-making.

IPADeP has been applied to sub-systems and components of DEMO tokamak, providing a valid support for conceptual design activities under development, as discussed in the case study section of this thesis.

1.1 Objectives and contribution

Basing on the experience in fusion reactor sub-system development, the primary objectives of this research is to investigate and propose a design process for the development of system concepts. The goal is to propose generic process for large-scale engineering design, not only limited to the fusion application presented.

In order to overcome the difficulties discussed in the previous section related to the conceptual design, in this research it is proposed a design process for drafting solutions in an “incomplete requirements environment”. The IPADeP process is an iterative and incremental, participative process, requirements driven. It aims to provide a systematic process to face the conceptual design activities minimizing the risk related to the uncertainty and incompleteness of the requirements and considering that the requirements will be refined and completed during the design process.

Accordingly, the second main aim of this dissertation is to discuss and demonstrate the advantages in using IPADeP in large-scale engineering system, in particular for the applications concerning the design of fusion tokamak reactors. Indeed the development of tokamak sub-systems has to take into account interface, structural, functional requirements and multi-physics issues that can be completely known only during the development of the process.

2 BACKGROUND

2.1 Systems Engineering

A “system” is a combination of different elements that together produce results not obtainable by the elements alone (Shishko and Aster 1995). NASA systems engineering handbook defines the systems engineering a “*methodical, disciplined approach for the design, realization, technical management, operations, and retirement of a system*”.

The INCOSE handbook (Haskins *et al.* 2006) provides the following definition:

“Systems engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem. Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs.”

From both definitions one can derive that systems engineering would establish an holistic perspective of problems and design, and would support designer in considering how systems fit into larger context, how they are influenced from the interfacing system, and what is the impact on them.

As can be inferred from the nature of earlier projects, the systems engineering discipline emerged as an effective way to manage complexity and changes, which both have escalated in the products, services and society.

Systems engineering is a way of looking at the “big picture” when making technical decisions(Shishko and Aster 1995) . It is a way of achieving stakeholder functional, physical and operational performance expectatios in the intended use environment over the planned life of the systems. In other words, systems engineering is a logical way of thinking. It aims to support the development of a system capable of meeting requirements within often opposed constraints, wherein the contributions of structural engineers, electrical engineers, mechanism designers, power engineers, human factors engineers, and many more disciplines are evaluated and balanced, one against another, to produce a coherent whole that is not dominated by the perspective of a single discipline.

The international standard ISO/IEC 15288 (Arnold 2002) provide a defined set of processes to facilitate communication among acquirers, suppliers and other participants in the life cycle of a system and establishes a common process framework for describing the life cycle of man-made systems. It defines a set of processes and associated terminology for the full life cycle, including conception, development, production, utilization, support and retirement. The standard also supports the definition, control and assessment, which can be applied concurrently, iteratively and recursively to a system and its elements throughout the life cycle of a system.

The systems engineering process has an iterative nature that supports learning and continuous improvement. As the processes unfold, systems engineers uncover the real requirements and the emergent properties of the system. Complexity can lead to unexpected and unpredictable behavior of systems, hence, one of the objectives is to minimize undesirable consequences. This can be accomplished through the inclusion of and contributions from experts across relevant disciplines coordinated by the systems engineer.

The systems engineering perspective is based on systematic thinking. *"Systematic thinking occurs through discovery, learning, diagnosis, and dialog that lead to sensing, modeling, and talking about the real-world to better understand, define, and work with systems."*(Haskins *et al.* 2006)

A number of methodologies, processes and tools consistent with system engineering principles are used by engineers to develop complex systems.

Overall any SE method should respond to the following questions:

- Which requirements have led to a certain solution and what is their source?
- If this requirement were to change, what should be revised?

- Is everything documented and are all documents traceable?
- Are all requirements SMART defined (specific, measurable, achievable, relevant and traceable)
- and are we compliant?
- Does our product contribute effectively to the objectives of our customer?

INCOSE (Haskins *et al.* 2006) defines the System Life Cycle in six stages, providing a framework for meeting the stakeholders' needs in an orderly and efficient manner. Then for each life cycle stage a set of tools/methodologies/process should be used to support the engineering activities and to allow for meeting the stage's objectives. This research is placed in this contest, proposing an integrated methodology to increase concept development effectiveness by means of a disciplined approach to collaborate within interdisciplinary teams.

2.1.1 Life cycle stages

"A life cycle model that is composed of stages shall be established. The life cycle model comprises one or more stage models, as needed. It is assembled as a sequence of stages that may overlap and/or iterate, as appropriate for the scope, magnitude, and complexity, changing needs and opportunities (Haskins *et al.* 2006) ."

In a system engineering approach a life cycle model can be established as a sequence of stages that may overlap and iterate according to scope, needs and opportunities of the system . According to the ISO/IEC 152883 every manmade system has a life cycle. INCOSE (Haskins *et al.* 2006) defines six life cycle stages, with predefined levels of development, in order to establish a framework for meeting the stakeholders' needs in an orderly and efficient manner (Table 1).

Table 1: Systems Engineering lifecycle stage

LYFE CYCLE STAGES	PURPOSE	DECISION GATES
CONCEPT	Identify stakeholders’ needs Explore Concepts Propose viable solutions	Decision Options: – Execute next stage – Continue this stage – Go to a preceding stage – Hold project activities – Terminate project
DEVELOPMENT	Refine system requirements Create solution description Build system Verify and validate system	
PRODUCTION	Produce systems Inspect and test	
UTILIZATION	Operate system to satisfy users’ needs	
SUPPORT	Provide sustained system capability	
RETIREMENT	Store, archive or dispose of the system	

Using stages concurrently and in different orders can lead to life cycle forms with distinctly different characteristics. Organizations employ stages differently to satisfy contrasting business and risk mitigation strategies. The selection and development of such life cycle forms depend on several factors, including the business context, the nature and complexity of the system, the stability of requirements, the technology opportunities, the need for different system capabilities (Arnold 2002).

As an example, United States Departement of Defense (DoD) was one of the first organization in rigidly defining life-cycle stages, structuring the management process into discrete phases separated by major decision point. In this model, shown in Figure 2, the materiel solution analysis is the first phase and contains the identification of potential solutions, the analysis of alternatives and the examination of operational concepts. In such a way, this phase is the equivalent of the conceptual development stage discussed in this thesis.

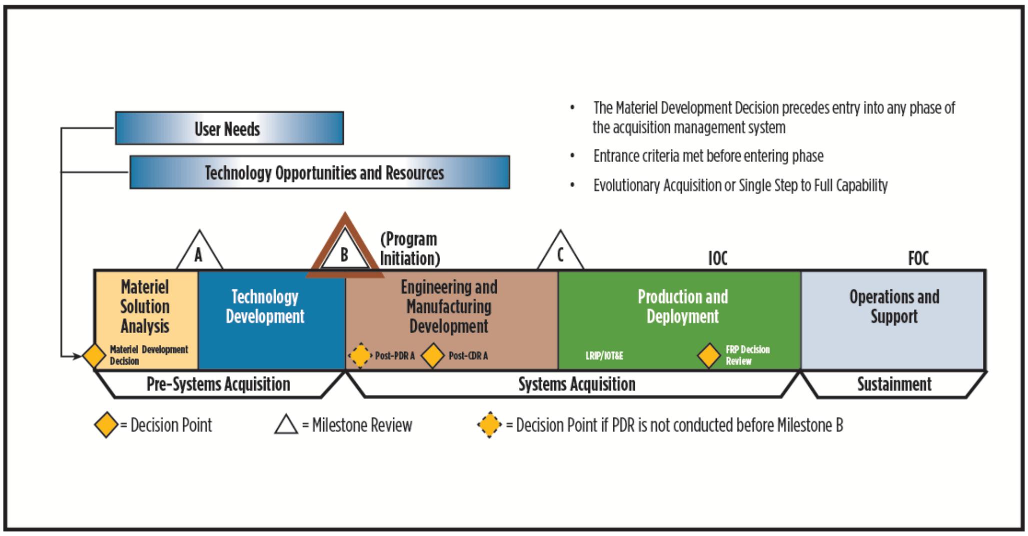


Figure 2: DoD Project Lifecycles (Under USA Secretary of Defense, 2008)

Also NASA (Natonal Aeronautics and Space Adminisration) has its own lifecycle model and milestones (Figure 3).

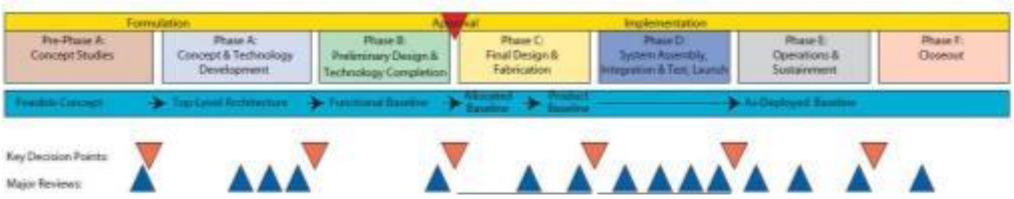


Figure 3: NASA Project Lifecycles (Shishko and Aster 1995)

In the Pre-Phase A, a wide range of alternative ideas are generated and evaluated, aiming to determine system feasibility, identify system requirements and potential technology needs (Kapurch 2007). Phase A has the objective to define the final mission concept and the technology development plans.

The framework proposed in this research could be through NASA Pre-Phase A and Phase A, driving from a number of information and alternatives considered to as smaller range of solutions.

The research activities presented in this thesis were mainly focused on the development of a design process for the conceptual design stage of fusion reactor components. Within the tokamak machine engineering activities, the International

Thermonuclear Experimental Reactor (ITER) (Pizzuto *et al.* 2010), actually under construction, provided systems engineering approach for the design.

The project life cycle shown in Figure 4 refers to ITER project, for the development and realisation of its systems or subsystems. The system life cycle is characterized by some decision gates. The decision gates determine readness to move from one stage to the next. Skipping phases and eliminating "time consuming" decision gates can greatly increase the risks (cost and schedule), and may adversely affect the technical development. Decision gates represent major decision point in the system life cycle. They ensure that new activities are not pursued until to previously scheduled activities, on which new ones depend, are satisfactorily completed and placed under configuration control. Decision gate approval follows review by qualified experts and involved stakeholders and is based on hard evidence of compliance to the criteria of the review. There are at least two decision gates in any project: authority to proceed and final acceptance of the project deliverable (Haskins *et al.* 2006). The project team needs to decide which life cycle stages are appropriate for their project and which decision gates beyond the basic two are needed.

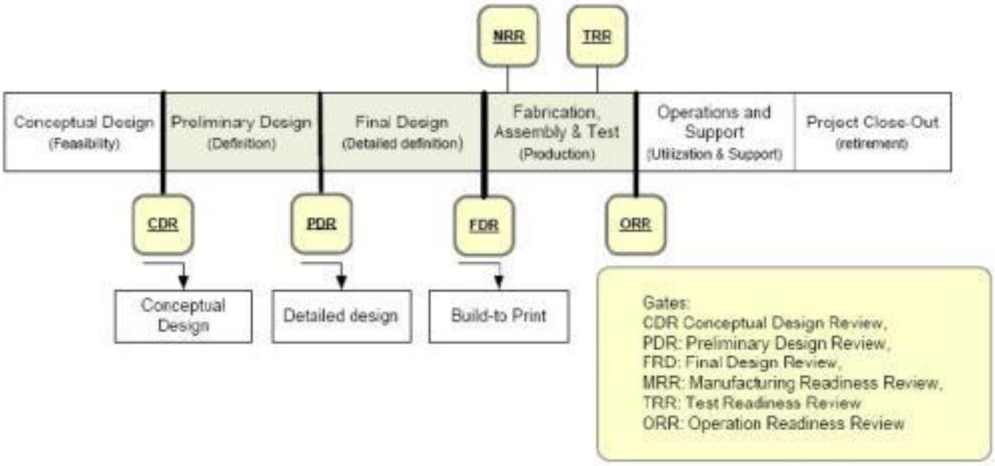


Figure 4: ITER lifecycle stage

2.1.2 Conceptual Design Stage

Purpose: The Concept Stage is executed to assess new business opportunities and to develop preliminary system requirements and a feasible design solution.(Forsberg and Mooz 1991).

During the Concept Stage, the team begins the identification of stakeholders' requirements, the development of alternative solutions meeting the defined requirements and the evaluation of multiple candidate concepts, eventually providing a substantiated justification for the system concept that is selected. During this first evaluation digital mock-ups may be built and simulations may be performed to verify the feasibility of concepts and to explore risks and opportunities. Furthermore, early validation efforts help in requirements refining and definition. The systems capabilities specified by the stakeholders will be met by the combination of system elements. The system function then must be decomposed and allocated to individual components. The issues related to each part should be addressed early to minimize the risk that, when these entities are finally designed, verified and assembled in a whole system, they fall short of the required functionality or performance. Many studies identified a root cause of system failure in insufficient or superficial studies during the concept stage.

The conceptual design phase first triggers the iterative process that develops and analyses concepts and alternatives available for meeting the approved "mission need". In conceptual design, top-level functional requirements are developed and documented. Trade studies are conducted which facilitate decision making between configuration options. An overall design concept that meets the functional requirements is developed. Concept designing begins from concept generation based on defined requirements. During concept design phase new requirements can be noticed and some of them can be changed. Requirements are not static and one reason for that is learning and better understanding of the design concept and its environment during design process. This represents a key issue in the early design development phase and this is why requirements management and concept development process are strictly interrelated, as discussed in the following sections.

2.1.3 Technical processes

The product development is supported by the technical processes, which are invoked throughout the life cycle stages of a system. SE processes generally begin with the development of requirements for the system as the basis for the efforts to create an effective product or service. Figure 5 shows the activities that can be performed during the life cycle of a system according to ISO/IEC 15288, where activities are divided in four processes group:

- Agreement processes;
- Enterprise processes;
- Project processes;
- Technical processes.

Focusing on the technical processes, ISO 15288 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.

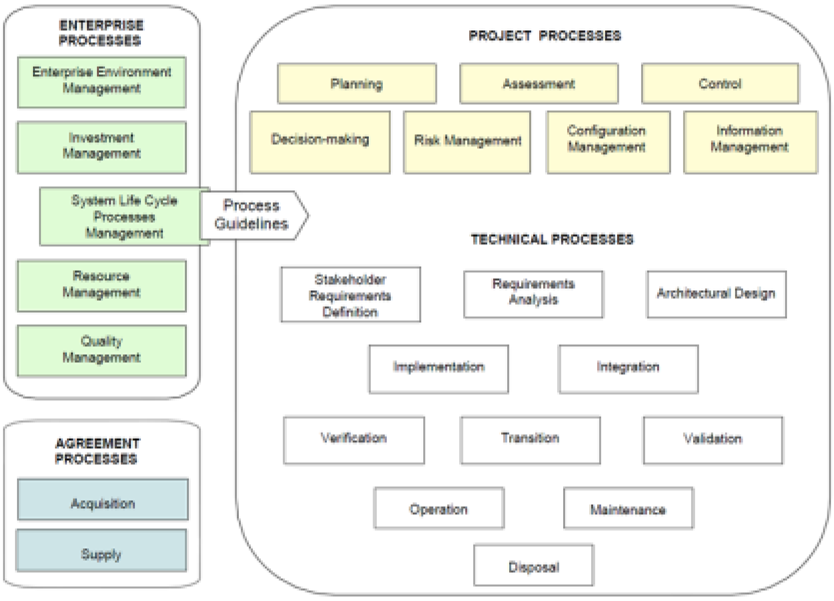


Figure 5: System Life Cycle Processes Overview per ISO/IEC 15288

Several alternative model exists to visualize technical processes and organize systems engineering development and management.

The Figure 6 shows a way to represent the technical processes, which is identified in technical literatures as the V model. First developed by Forsberg and Mooz in the 1980s (Forsberg *et al.* 2005), the V model is used to visualize the systems engineering focus, particularly during the concept and development stages. It 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.

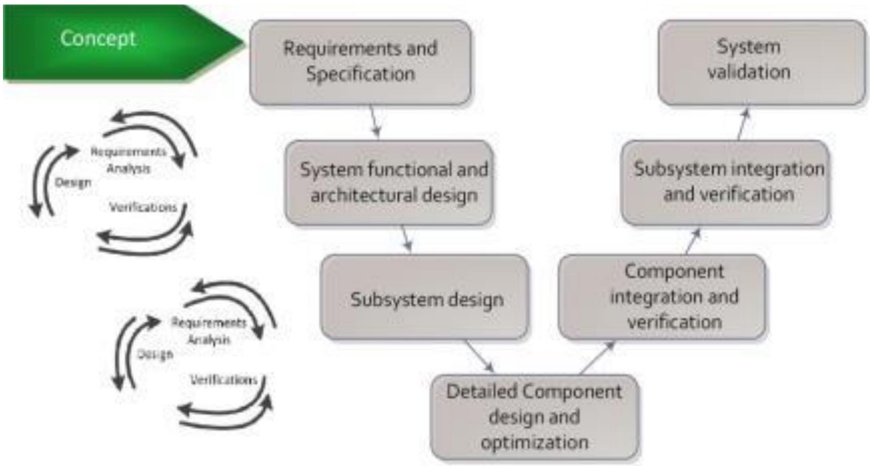


Figure 6: V-model

In the V model, time and system maturity proceed from left to right. The core of the V depicts the baseline from user requirements agreement to identification of a system concept, to the definition of systems components that will comprise the final product. With time moving to the right and with the system maturity shown vertically, the evolving baseline defines the left side of the core of the V. As entities are constructed, verified and integrated, the right side of the core of the V is executed. It provides a useful illustration of the systems engineering activities during the life cycle stages. It starts with the objectives input from the perspectives of the system acquirers. They hold a point of view of a system and its functions from the vantage point of the system owner and customer who have envisioned the system-to-be (Goetz and Rupp 2003). This perspective is highly needed for guiding technical aspects under the V lifecycle. The assumption is that the elicited requirements provide all necessary information needed to move forward. The iteration of requirement analysis and architectural design process is conducted through a perspective of a system engineer that encompasses all technical aspects of a system, including subsystems, components, and item specifications. The requirements analysis must be closely integrated with the other tasks throughout the activity. It may not be needed to establish all design criteria during the initial stages; however, the necessary design criteria should be fixed before starting the related level of design. No design can be completed before establishment of the system requirement documents reflecting all relevant design inputs. The development of alternatives, the selection of a balanced solution, and the description of the solution as a design package is accomplished via design definition and systems analysis and control.

ITER Systems Engineering Management plant, consistently with the provisions from INCOSE, proposed a set of technical processes represented as a V-model as shown in Figure 7 .

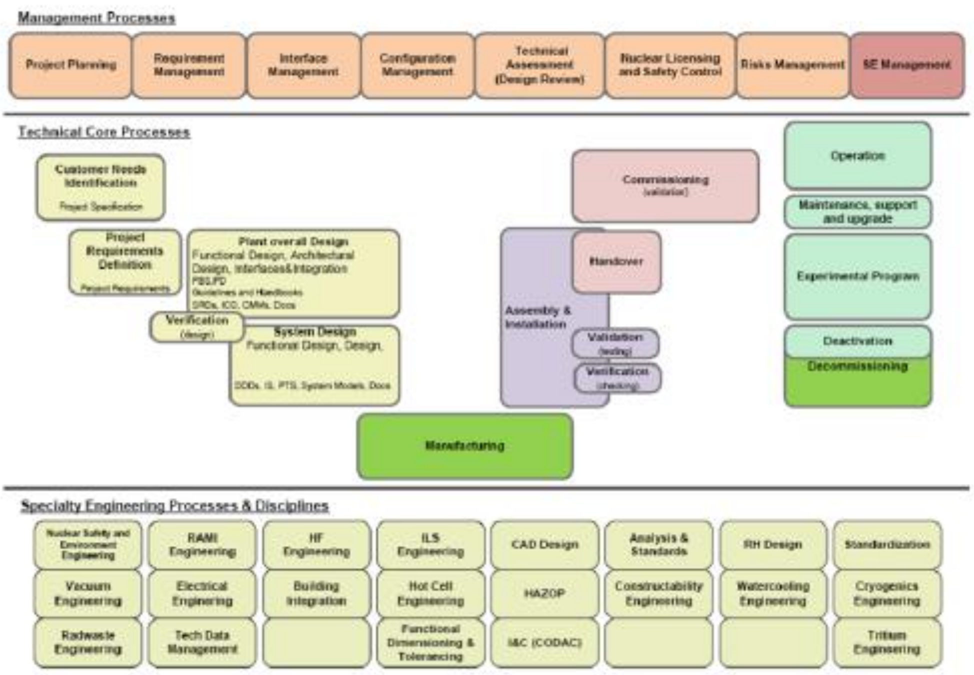


Figure 7. ITER Systems Engineering Processes

For DEMO fusion reactor the set of Technical Processes, based on the experience of ITER, is under definition. The activities presented in this research are placed in this contest, providing a design process for conceptual design of DEMO tokamak components.

The spiral model have the same phase of V model, but explicitly accounts for risk and re-evaluation. The most projects are not well suited to sequential process but require a number of iterations (Maier 2009). In the spiral model, shown in Figure 8, there is a built-in risk management, which reduces the “cumulative cost” of the product, by rectifying mistakes at an early stage during project lifecycle. Designers work through each phase in each iteration. The angular sections represents progress, while the radius of the spiral represents maturity (Boehm 1988).

The first cycle is often focused on assessing the aspect of the design with most risk, starting from the more abstract level. This is useful in situations where requirements cannot be fully defined prior to system design, or if immature technology is required. The model assumes that missing requirements or technology viability will be revealed after each spiral iteration. At the completion of the first loop a solution is proposed, and each subsequent spiral builds upon this defined baseline.

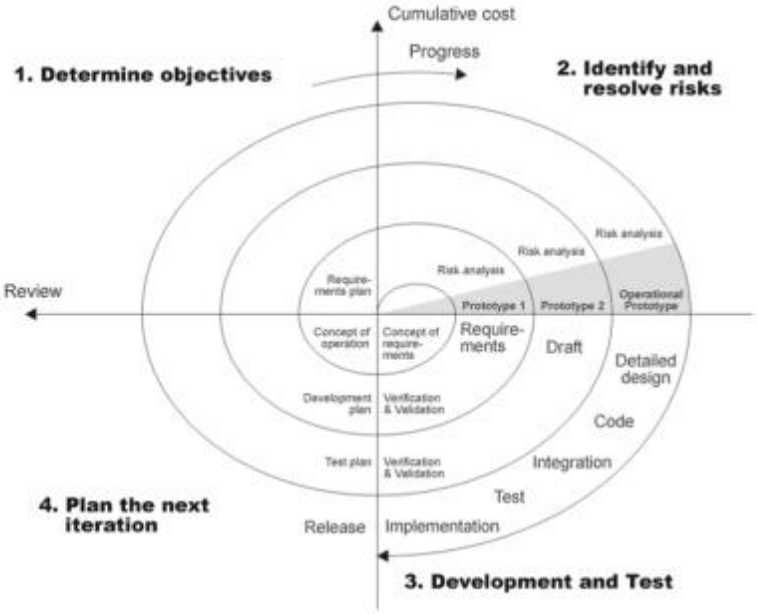


Figure 8. Spiral Model

2.2 Requirements management

Within the context of ISO/IEC 15288, requirements are specifically mentioned in two of the technical processes, and 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 customer. 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. Requirement elicitation is an iterative activity and benefits from continuous communication and validation with the customer. Creation or upgrade of a system shares the same uncertainty regarding future use and emergent properties of the system. This will enable the traceability from a solution to the requirements that lead to the design. All the requirements are defined in a specific, measurable, realistic and time-based manner. Therefore, if some requirements were to change, it will be clear links to the corresponding designed feature. This ensures the final designed product contribute effectively to the objectives of the customer.

In this thesis a design process for drafting solutions in an "incomplete requirements environment" was developed, as may occur in complex projects during the early conceptual design stage. 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.

Requirements development is not only the initial part of the system life cycle, but it is connected to the whole product life cycle, and requirements evolve across the various level of PLC. Nowadays Requirements Management (RM) will be the key for success to achieving the goals and target in a project. The use of the requirements engineering and management is becoming widely practiced in the mechanical design. RM keep track of the initial requirements and changes made to it during plc. Requirements play a vital role in every stage of system development; i.e.

requirements create the ground of system development process. In advanced development phase requirements are used to identify components that require more development (Ambriola and Gervasi 1997).

Requirements Engineering is wide engineering branch and it shall be examined carefully in Concept Development phase. Hull, Jackson, and Dick have presented comprehensive theory of Requirements Engineering in (Hull *et al.* 2010) that will be partly applied in this development process. Requirements are divided into different levels, depending on their specificity.

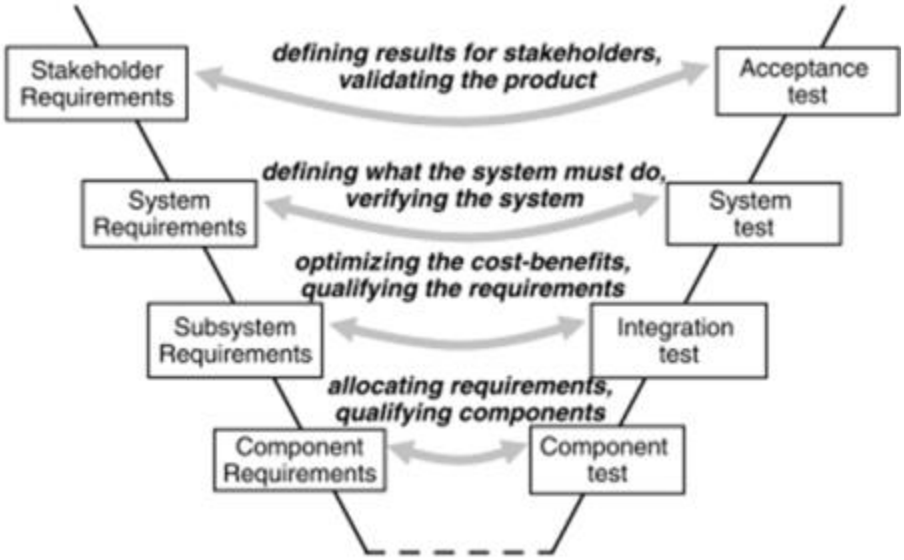


Figure 9. V model for requirements engineering

In Figure 9 is the classical V-model that presents the various layers in system development process: requirements are at the left side and tests are at the right side. Requirements are derived from high level requirements (stakeholder requirements) to lower level requirements (system, subsystem and component requirements). The links between various requirements in the development process is maintained by tracing requirements between different layers, i.e. traceability. Links between requirements and test are maintained by qualification actions i.e. Verification and Validation.

Traceability

Maintaining of traceability of requirements is mandatory in complex system development process that has many different requirements at various layers. Traceability contributes many benefits in development process and the most beneficial is that it "allows greater confidence in meeting objectives. Establishing and formalizing traceability engenders greater reflection on how objectives are satisfied" (Hull *et al.* 2010). The main purpose of traceability is to maintain the links between various requirements. Furthermore, traceability indicates how requirements are satisfied i.e. it keeps also the links between test and requirements.

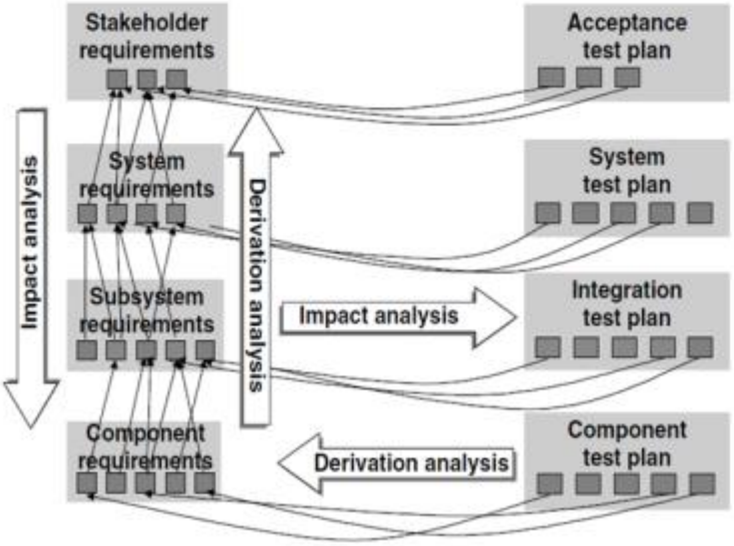


Figure 10. Requirements traceability (Hull *et al.* 2010).

As Figure 10 illustrates, requirements and tests are closely related at every layer. According to Hull et al. "testing can be described as any activity that allows defects in the system to be detected or prevented, where a defect is a departure from requirements"(Hull *et al.* 2010) .

2.3 Change Management

The traditional practice of systems engineering management involves the determination of requirements at or near the beginning of a system development project (Haskins *et al.* 2006). All subsequent steps are dependent upon the completeness, accuracy and specificity of these requirements. However, as stated above, in large-scale engineering systems usually the design process starts when the requirements are not completely defined from the beginning and the information contribution from the various working groups comes into the project during the design activities. We argue that, 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.

Methods and computer aided system have been developed, aiming to assist the definition of design requirements, the concept generation and the evaluation during the conceptual design, when the impact of making good decision is very high, but the availability and capability of methods and tools is very low (IMTI 2000). Many of these methods are based on the assumption that the optimal design identified doesn't change during the different phases of the design process. Furthermore, most design groups use local and segmented approach when developing large-scale engineering systems, that cannot provide an effective management of requirements and design changes.

The management of engineering and requirements changes during the design development of complex system is attracting researcher attention and several authors discussed about design and requirements change impact (Clarkson *et al.* 2004), (Eckert *et al.* 2009) (Giffin *et al.* 2009). Change Management is the processes that define how changes are managed throughout the development life cycle. Change Management includes management of change requests, validation and evaluation of change requests, adjudicating and approving change requests, and implementation of the change request. Changes could refer to requirements, design, implementation or testing.

When the customer requirements change during the design effort, it is generally not feasible to restart the design process from scratch, so new and modified functional requirements and constraints must be incorporated into the existing design as the changes occur. The lack of a systematic framework to trace the impact of changing requirements and design decisions can lead to inaccurate impact analysis, estimates and a breakdown of proper communication between the stakeholders. One design team may not be aware of changes occurring to another group's requirements, even though they are significantly impacted (Hintersteiner and Zimmerman 2000).

2.4 Systems engineering tools

2.4.1 System Modelling & Requirement Identification

Many types of model have been developed to describe a system, most of which are defined in the Systems Modelling Language (SysML) (Cao *et al.* 2013).

The *Context Diagram* (AKA Boundary Diagram) (Kossiakoff *et al.* 2011) displays the external entities of the system and their interactions/interfaces with the system. Such a diagram pictures the system at the centre, with no details of its interior structure (i.e. a "black box" representation), surrounded by its interacting external entities. The objective of the Context Diagram is to focus attention on external factors and events that should be considered in developing the systems requirements and constraints.

The Context Diagram consists of 3 components:

- External Entities: all the entities with which the system will interface or interact, both directly and indirectly
- Interactions: An interaction between the system and an external entity is represented by a line linking the two.
- The System: Represented by a single geographic feature, typically a box in the middle of the diagram containing just the system name

One exceptionally useful function of the Context Diagram is that it implicitly defines the system boundary and thereby communicates it to the system designers, stakeholders and project management. This aids the system integration process, where it is important that all interfaces are identified and managed to avoid confusion or absence of responsibility for components or functions within a system. To help define the boundary even further it may be useful to supplement the Context Diagram with a system architecture schematic (being careful not to overly define the internal system design if possible) with a clearly defined visual boundary around the system and defined flows (physical, data, power etc.) across the boundary.

In identifying the stakeholders' needs, it can be helpful to try and apply the "*onion model*" to the diagram, as shown in Figure 11 and described by Alexander (Alexander 2006). Grouping stakeholders in appropriate categories aids in identifying missing stakeholders and hence in achieving a complete diagram.

Figure 11. Onion Model for Requirements

In identifying the main systems functions and the related design driver, the Functional Flow Diagram (FFD) is very helpful. FFD is a network representation of the system in terms of its component functions and the interdependencies or "flows" between them. It is an abstract view of the system and hence flows can represent matter, energy, information (data), control signals etc.

The FFD highlights the potential or logical interfaces between functions, i.e. logic/common sense says there should be a flow. Some of these logical interfaces will become real interfaces, and hence FFDs are a good starting point for identifying system internal interfaces.

Flows do not necessarily indicate movement – they just indicate that a particular function requires a flow as an input, or produces a flow as an output.

The ***IDEF0*** standard (Colquhoun *et al.* 1993) provides a more formalised method for constructing and representing Function Flow Diagrams (FFDs). The basic building block is shown in Figure 12; the system function is shown in the box and the interlinking arrows represent flows between the functions, which is exactly the same as the FFD building block. However, the syntax is more strict: Inputs are shown as arrows entering the left side of the activity box while output are shown as exiting arrows on the right side of the box. Controls are displayed as arrows entering the top of the box and mechanisms/calls are displayed as arrows entering/exiting from the bottom of the box.

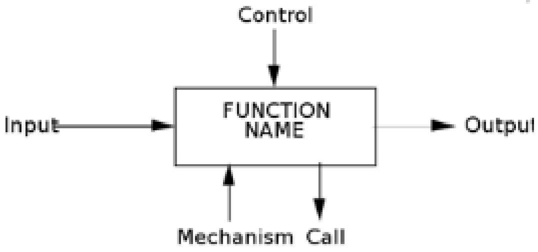


Figure 12. IDEFO diagram

As with FFDs, IDEF0 diagrams are intended to be nested, as shown in Figure 13.

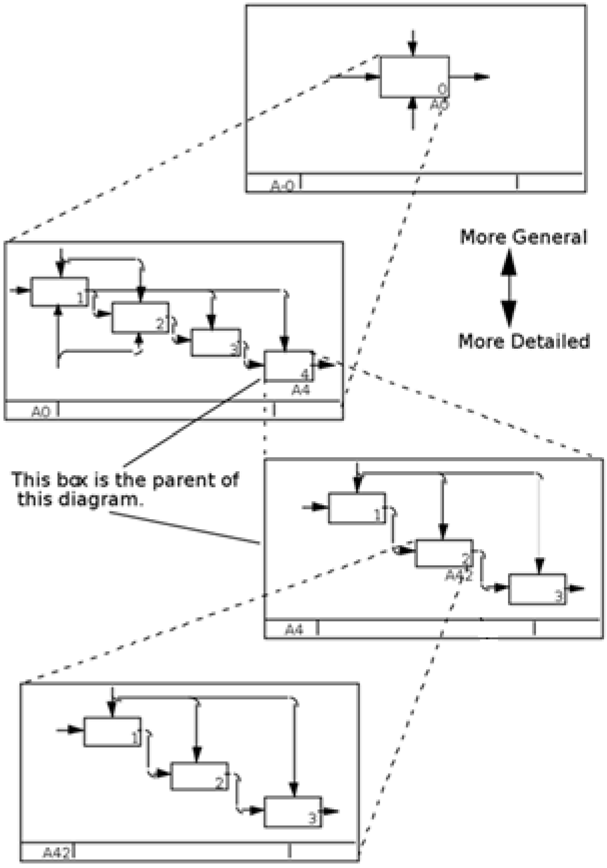


Figure 13. IDEF0 hierarchical structure

IDEF0 has been used in this research for systems functions and interfaces identification, as discussed in Chapter 3 and in the case study (Chapter 4).

2.4.2 Design methods for concept development

Concept development is focused on identifying a design to maximize stakeholders value over the system lifetime. A number of different mechanisms exists to help engineers in developing concept solutions and determine the best alternative. As the complexity of systems increase, the attention of industry and academia in design methods supporting the concept development is gradually increasing, seeking benefits from development lifecycle approaches and design methodologies.

One simple definition of design is that a design process converts a need, expressed as an abstract concept in terms of functionality, into product (system, device service or process) satisfying that need. The process is a complex one that requires the designer to exercise initiative and creativeness as well as deploy a wide range of skills, methodologies and expertise in attaining a solution.

Deign 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 (Albano 1999). Suh (Suh 1990) 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 (Suh 1990). 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 (Suh 2001). 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 and Nordlund (Tate and Nordlund 1996), 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.

According to Suh (1990) all design activities must do the following:

1) Know the "customers' needs".
2) Define the essential problems that must be solved to satisfy the needs.
3) Conceptualize the solution through synthesis, which involves the task of satisfying several different functional requirements using a set of inputs such as product design parameters within given constraints.

4) Analyse the proposed solution to establish its optimum conditions and parameter settings.
5) Check the resulting design solution to see if it meets the original customer needs.

In addition to these activities, we note that, as stated also by Helander and Lin (Helander and Lin 2002), in the conceptual design activities of large systems a design method should:

6) Provide a consistent, quantitative method to face the choice among alternative design.

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. Several design methods and theories are available in literature, some focusing on concept generation and selection, such as Robust Engineering (Taguchi methods) (Taguchi and Phadke 1989), Theory of Inventive Problem Solving (TIPS/TRIZ) (Altshuller 1989), Total Design (Pugh 1991), others helping the requirement management and quality development such as the Structured Analysis and Design Technique (SADT) (Ross 1985) and the Quality Function Deployment (QFD) (Clausing 1994), others highlighting the steps to be performed during the design development such the Pahl and Beitz's method (Pahl *et al.* 2007), VDI 2221, and the WDK school (Hubka's theory) (Hubka and Eder 2012). The Axiomatic Design (AD) (Suh 1990) 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.

Each project team could select the most appropriate method to the organization and to the problem. Cavallucci and Lutz (Cavallucci and Lutz 2000) proposed also an Intuitive design method, in which several methods are integrated based on their strong point analysed considering four essential phases: collection and analysis, creation, construction and growth. Most of the development lifecycle approaches describes a set of activities/phases and some prescribes patterns of activities. There are very few design and development lifecycle methodologies that also provide some structured and systematic approach to capture and manipulate data used and produced by the development lifecycle activities.

Several authors have dealt with change in engineering, and according to (Jarratt *et al.* 2011) 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 (Clark 1991),(Anderson and Pine 1996). Companies usually integrate their customers in the design process and use instruments, such as Quality Function Deployment (QFD) (Hauser and Clausing 1988), to build up a clear picture of their requirements to avoid later changes (Eckert *et al.* 2009). A the same time, companies apply the classical systems engineering V-model and test products virtually as soon as possible (Jarratt *et al.* 2011). To generate Functional Requirements (FRs) and concepts at an abstract level QFD is an effective tool (Melemez *et al.* 2013), but it can be difficult to select and specify design alternatives at a more detailed level (Thielman and Ge 2006). On the other hand, to produce high-quality design alternatives at a parametric level Taguchi’s robust design principles (Taguchi *et al.* 2000, Wu and Wu 2000), have been widely used, but according to Thielman and Ge (Thielman and Ge 2006) 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) (Suh 1990), (Suh 2001). AD deals with most of PDL activities, but it does not support the whole PDL (Tate and Nordlund 1995). 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. 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 (Gumus *et al.* 2008). 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 application of the AD theory in a nuclear reactor system (Thielman and Ge 2006) (Kim and Cochran 2000)demonstrated that this methodological approach represents a viable method for large-scale engineering systems development.

In this research AD and APDL are assumed as support methodologies for the development of a design process dealing with the main issues related to the conceptual design stage. AD principles could be also well integrated with other methodologies, as for example TRIZ to improve the concept generation step (Kim and Cochran 2000) and other methods for concept selection.

2.4.2.1 Axiomatic design

The Axiomatic Design provides a systematic approach to design by introducing some axioms and theorems, and also concepts such as domains, zigzagging, and design matrices.

Chen (Chen 1999) states that the AD is the method that illustrates design process and design method clearly whereas other design methods such as optimization design, robust design, reliability design, and design for X, may belong to a kind of method for mapping between a special design requirement and its design solution in the process of AD.

AD provides a systematic approach to the design activity from the early stage. Several authors consider it the most useful design methodology to deal with the early conceptual design (Sozo *et al.* 2001), (Xue *et al.* 2006), (Morrison *et al.* 2013) and different application of AD during conceptual design are available in literature, in the ergonomics design (Helander and Lin 2002), glass bulb design (Do and Park 2001), large-scale systems design (Thielman and Ge 2006), mechanic parts design (Muzakkir *et al.* 2015), mechanical assemblies design and structural design (Albano 1999).

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 (Suh 1990)and (Suh 2001). There are four main items in AD: (I) domains, (II) hierarchies, (III) zigzagging and (IV) design axioms, schematically shown in Figure 14. 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.

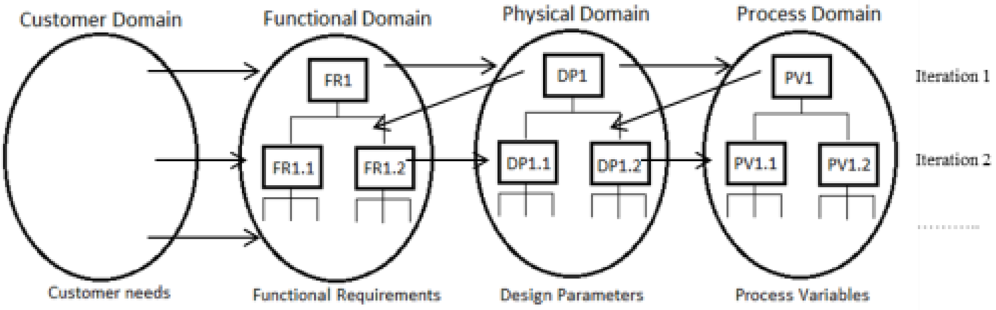


Figure 14. AD Domains

There are two axioms in AD, to support analysis, which can be stated as follows :

- 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:

$$FRs = [A] \quad DPs$$

where [A] is the design matrix that characterizes the nature of the mapping. An X or O in a elements indicates whether the column’s DP affects the row’s FR or not. Instead of a simple X or O, each cell can contain the mathematical relationship between the FR and the DP. The design matrices contain a wealth information about the design and are central to the application of AD.

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.

It is very important to know that the design matrix may satisfy the first axiom at conceptual design levels, however, the design decisions at lower levels ultimately determine if the system design satisfies the first axiom. Therefore, full design matrix that represents all FRs and DPs should be formed at each level of decomposition and make sure that the functional independents is still maintained.

At each level of decomposition, master or multi-level design matrix is formed to evaluate the consistency of the design as well as to ensure that the higher level design decisions and assumptions are still valid (Lee 1999). The system architecture can be used as a communication tool between different design teams and other stakeholders. A SA should be developed for every systems to capture the performance requirements and components of the system in a logical, coherent, and comprehensive manner, to facilitate communication between engineers, managers, and other stakeholders including the customer, and to provide good technical documentation of the design decisions made and the reasoning behind them (Hintersteiner and Zimmerman 2000).

2.4.2.2 Axiomatic Product Development Lifecycle

Gumus (Gumus 2005) states that the AD method provides a robust structure and systematic thinking to support design activities, however, it does not support the whole product development lifecycle. The same logic and scientific thinking can be used and extended to capture, analyse, and manage the product development lifecycle knowledge. He propose the Axiomatic product development lifecycle that extend the axiomatic design method to cover the whole product development lifecycle including the test domain and new domain characteristic vectors are introduced such as the input constraint and system component vectors.

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 (Gumus *et al.* 2008). 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 Figure 15.

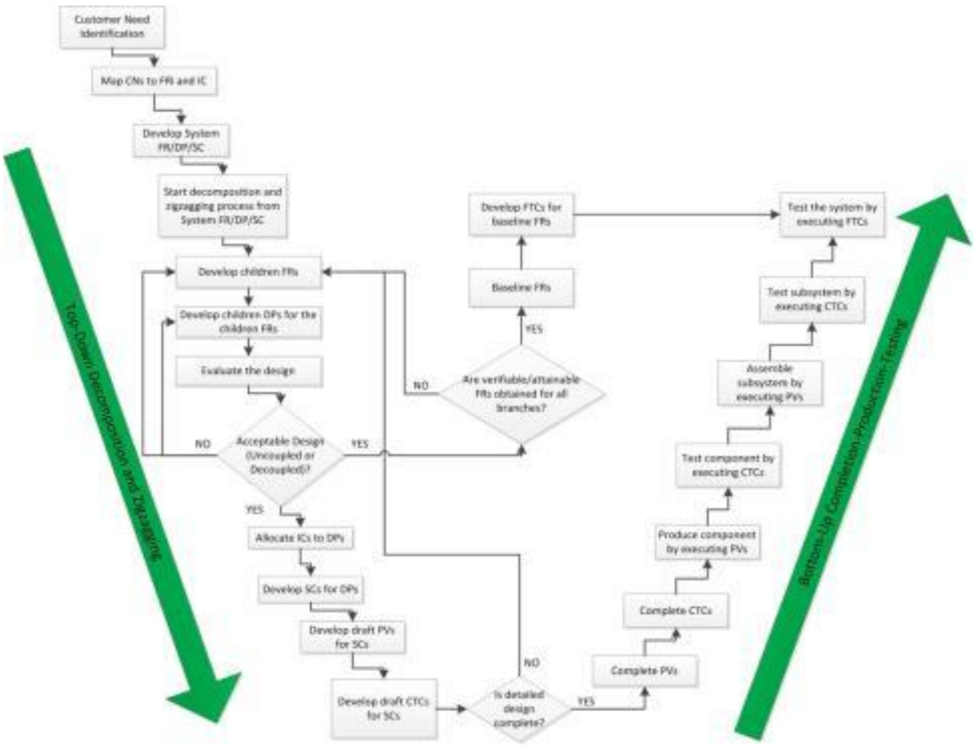


Figure 15. APDL V-model

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 (Gumus 2005).

2.4.3 Decision Analysis

Engineering decisions often require systematic evaluation of multiple options, based on a set of criteria. Several tools are available in literature and each one seeks to answer the same basic question: what are the potential solutions to the problem, how do they perform and which is the best one? (Borer *et al.* 2009)

Decision tree, Delphi method, Pugh Method and Analytic Hierarchy Process are among the most used Multi Criteria Decision Making (MCDM) technique. The AHP (Saaty 1980) provide the prioritization of design criteria and the pair-wise comparison of solutions against each criterion.

The AHP has been widely used by both researchers and practitioners in a MCDA where you have multi-criteria for decision making (Kannan and Vinay 2008). It has been proposed as a methodology to large, dynamic and complex real-world MCDA problems (Murat Albayrakoglu 1996).

However, considering the conceptual design stage, since decision maker's requirements may contain ambiguity and the human judgment on quality attributes may be imprecise (Di Gironimo *et al.* 2013), 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.

The first step of the procedure is to decompose the general problem into the following hierarchical structure (Figure 16):

- Goal to be obtained
- Quantitative and qualitative criteria
- Alternatives

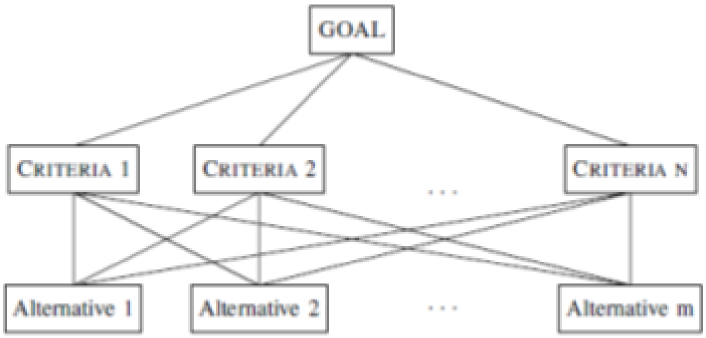


Figure 16. AHP Hierarchy structure

Generally, the goal can be the choice of the optimal solution. This solution has to be selected among a finite number of alternatives, with respect a finite number of evaluation criteria.

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 (reported in Table 2 and Figure 17).

Table 2. Linguistic Variables

Linguistic scale for importance	Abbreviation	Triangular fuzzy scale
Absolutely more important	AMI	(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)
Equally 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)

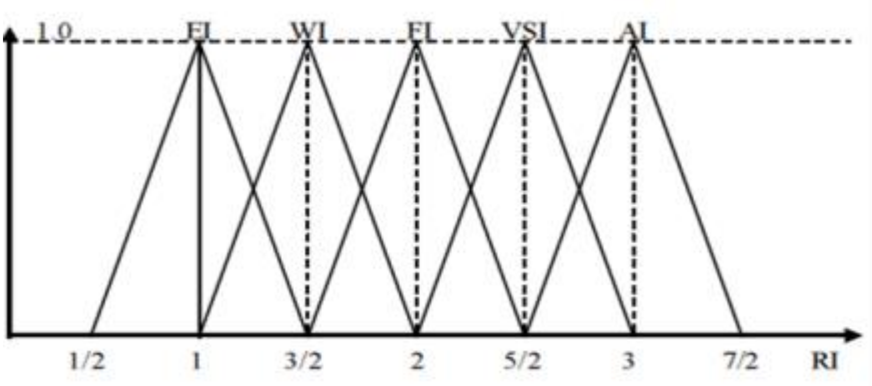


Figure 17. Fuzzy Numbers for linguistic variables

The answer from the judges obtained in fuzzy numbers are then processed according to the extent analysis (Chang 1996) to achieve the weights of each solution and identify the best solution.

2.5 Summary

The experiences reported in literature regarding complex systems design , as well as the experience performed during these research activities in developing tokamak fusion reactor components, highlighted that 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.

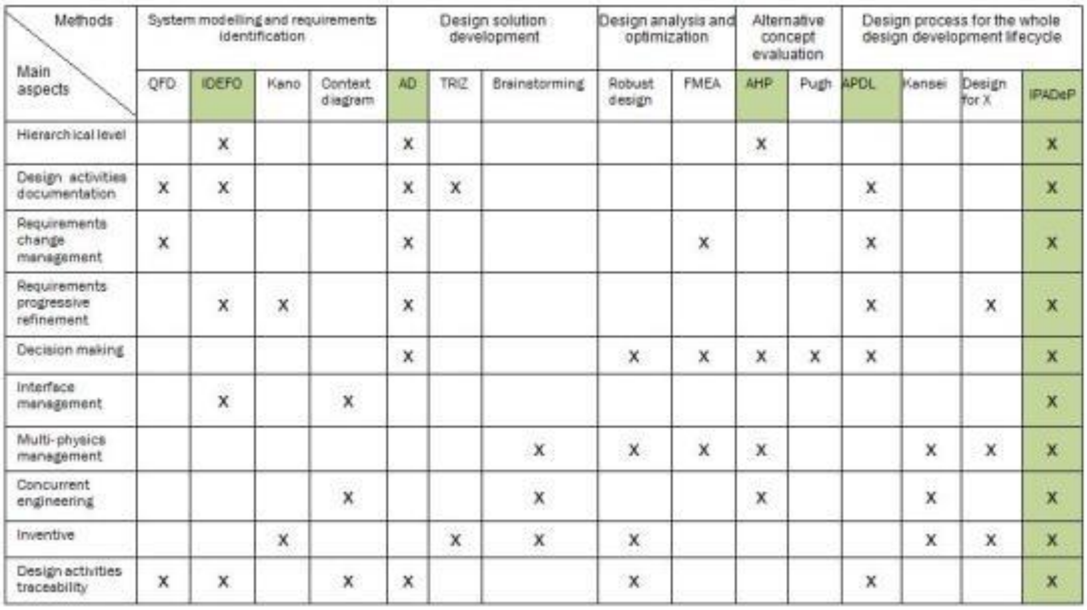
Basing on the studies of several SE methodologies available in literature in this research it is argued that an integrated design process to systematically deal with the conceptual design stage of complex systems need to be defined, aiming to:

- improve the concurrent engineering of the various sub-system components
- manage parallel development of interfacing sub-systems
- optimize the communication among distributed design teams
- manage continuous requirements refinement
- provide a process for requirements definition

- avoid re-design cycle
- support the virtual prototype testing and engineering optimization of design alternatives
- support the decision-making stage

Table 3 summarizes the main properties of the most used design methods. It highlights how the design process proposed in this research integrate the characteristics of different SE tools to provide a process dealing systematically with the main issue related to conceptual design of complex systems.

Table 3. Design Methods comparison



Methods / Main aspects	System modelling and requirements identification				Design solution development			Design analysis and optimization		Alternative concept evaluation		Design process for the whole design development lifecycle			
	QFD	IDEF0	Kano	Context diagram	AD	TRIZ	Brainstorming	Robust design	FMEA	AHP	Pugh	APDL	Kansei	Design for X	IPADeP
Hierarchical level		X			X					X					X
Design activities documentation	X	X			X	X						X			X
Requirements change management	X				X				X			X			X
Requirements progressive refinement		X	X		X							X		X	X
Decision making					X			X	X	X	X	X			X
Interface management		X		X											X
Multi-physics management							X	X	X	X			X	X	X
Concurrent engineering				X			X			X			X		X
Inventive			X			X	X	X					X	X	X
Design activities traceability	X	X		X	X			X				X			X

3 METHODOLOGY

3.1 Iterative and Participative Axiomatic Design Process

3.1.1 Motivations

As discussed in Chapter 2, Systems Engineering processes and most design methods are based on the assumption that at the beginning of the design process the requirements elicitation provides all necessary information needed to move forward. The iteration of requirement analysis and architectural design process is conducted through a perspective of a system engineer that encompasses all technical aspects of a system, including subsystems, components and item specifications. 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 a new process framework, the Iterative and Participative Axiomatic Design Process (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 stage of a “Customer need identification” (especially in the first iteration of the process) to the generation of the conceptual alternatives eventually leading to the selection of best alternative. Such a process should support efficiently and effectively the management of interfaces, in particular taking into account that interfacing sub-systems of a complex system are developed in parallel and are detailed as design proceed.

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.

As discussed in Section 2, 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.

Besides these general needs related to the design of complex system, during the research activities discussed in this thesis related to the design development of nuclear fusion reactor sub-systems, further issues have come to light.

A first point is that during the design process of a large-scale system, the first source of complexity resides in the identification of customers and stakeholders and their distinction. For a technical complex system the customers define, through statements, the system functions and its expected behaviour. In parallel, there are several stakeholders (technical partners, regulators, etc.) which provide a series of constraints and functional requirements (Table 4).

Table 4. Customer and Stakeholders needs definition

Customer	Systems functions	Design drivers
	Expected Behaviour	
Stakeholders	Sub-systems functional requirements	
	Interfaces	
	General 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.

As an example the initial design phase for systems that provide for a broader range of users, as for example a cruise ship, is mainly driven by the customers' needs and expectations and devoted to the explicitation and focalization of such needs. Alternatively, in the case of pure technical system, as for the chosen study case, i.e. a tokamak fusion reactor discussed in chapter 4, design activities are mainly driven by the technical requirements coming from the stakeholder needs. This two different categories of "needs" should be clarified and defined at the beginning of the design process, to improve the requirements understanding, their prioritization and traceability. 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. In general, it is possible to expect that during the design development of a complex system the customer needs do not change invasively, while the stakeholders' needs could continuously change and could be improved and detailed in the definition.

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 (Arnold 2002), as depicted in Figure 18.

As the system is decomposed, the requirements are also decomposed into more specific requirements that are allocated to the system components.

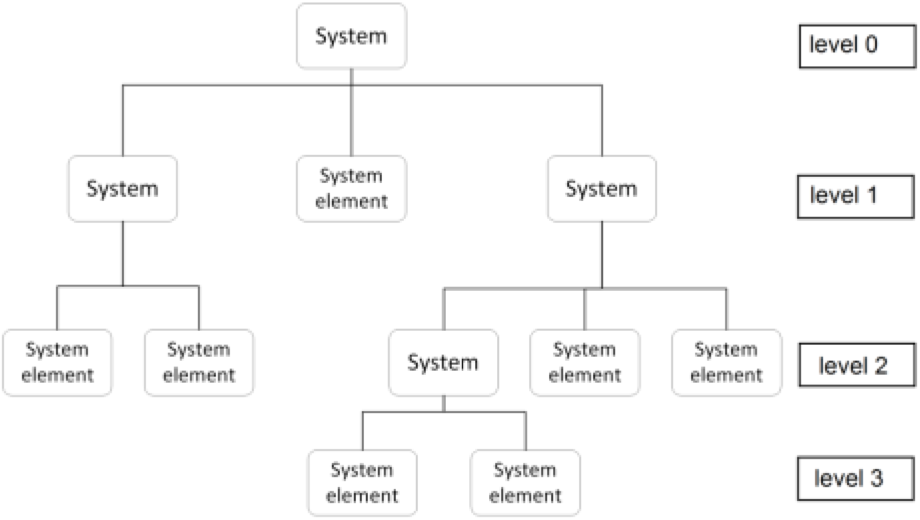


Figure 18. System structure

This implies the design process to be hierarchically structured and allow 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.

Based on these observations, in summary, the methodology developed and proposed in this research aims at to overcome the following point:

- Provide a framework to support systematic approach to the early stage of the design, dealing with uncertainty of information
- Provide framework for clear definition of needs and requirements
- Provide tools for design activities traceability and documentation
- Provide procedure for CAD design and analyses in the conceptual design

3.1.2 Iterative and Participative Axiomatic Design Process

The IPADeP flowchart is presented in Figure 19. Based on the APDL it has been developed according to the design process roadmap discussed by Tate and Norlund (Tate and Nordlund 1996) 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 conceptual design stage of complex systems if characterized by incomplete design information, since main requirements are continuously refined and updated from the other actors involved in the project during the design activities (i.e. interface requirements). However, 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 (Figure 15) 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.

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 as proposed by Gumus (Gumus 2005) to document the design and of the Master Design Matrix to evaluate the impact of requirement changes during the project.

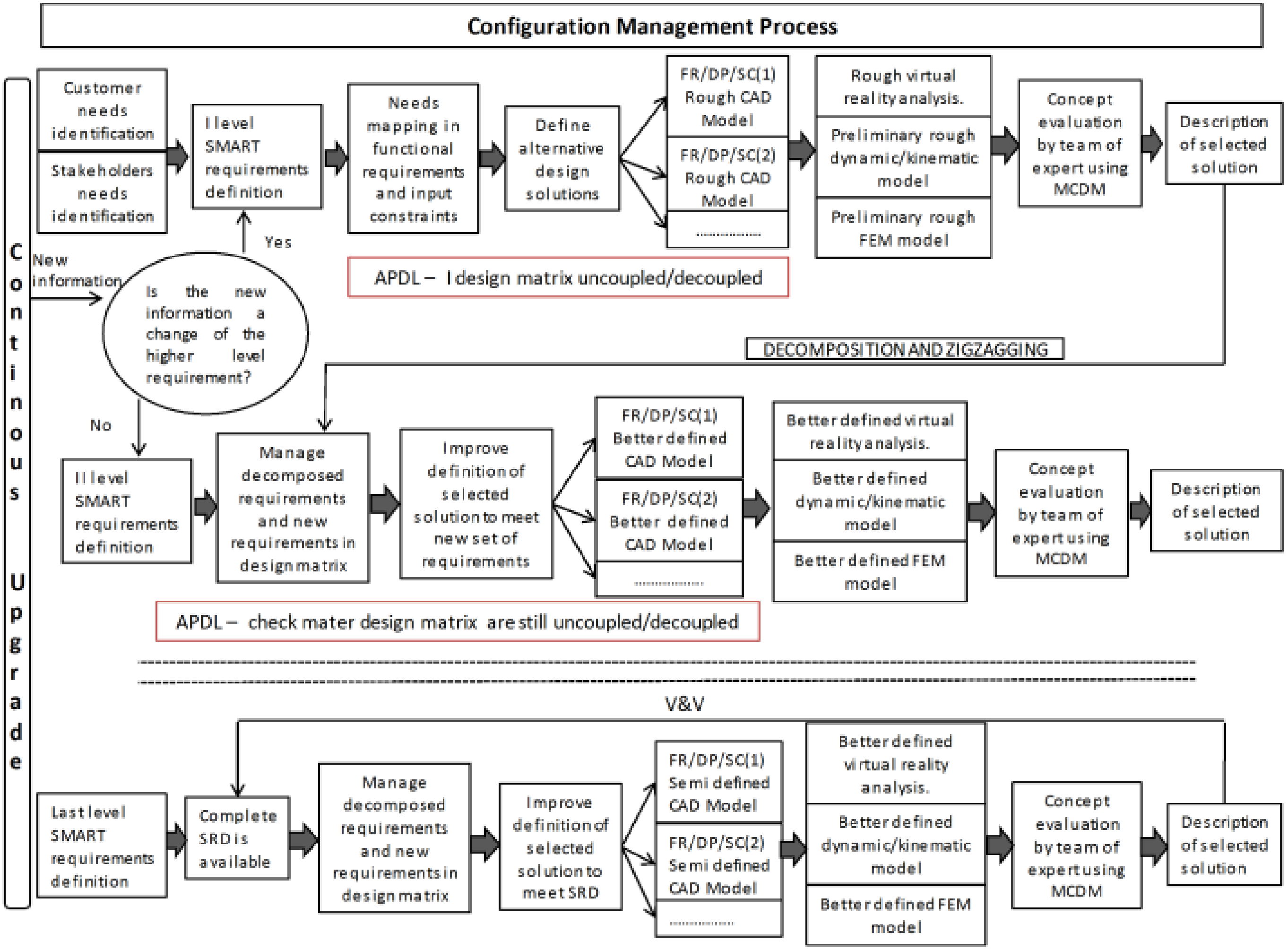


Figure 19. IPADeP Flowchart

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.

The process aims to improve the requirements definition stage and the hierarchical structure of the design process is highlighted as a main point to avoid re-design cycles and minimize the impact of requirements changes during the design activities. Figure 14 shows the traditional four-domain of AD and the decomposition and zigzagging process: for each level of the design process hierarchy, the new requirements imposed by the higher level design parameter selection are well handled by AD thanks to the decomposition process and the use of design matrices. However, as discussed above, during the design process of a large-scale complex system the information are continuously updated and improved and new requirements need to be managed and integrated (e.g. interface requirements). Differing from the requirements coming from the selection of an higher level concept solution, these requirements are not well handled by AD, and require the looping provided by IPADeP.

In the following sections, the first iteration of the process is discussed step- by – step, as well as the process through subsequent iterations. Then considerations related to the configuration management supporting the whole process are presented.

3.1.2.1 First iteration

The process starts with first iteration corresponding to the first level of decomposition. This phase is characterized by the highest level of abstraction for both the requirements and the design solutions proposed. As it will be exemplified in the case study presented in this research, at this level the information are very generic and lack of specific details that can be achieved only proceeding with the parallel design of the interfacing mechanical and physical sub-system making up the whole system.

1) Customer and Stakeholders needs identification

According to the needs presented in section 3.1.1, the process provides as first step the clear identification and distinction of the system's customer and stakeholders. This step is crucial for the correct development of the whole design process and for the success of the system. The customer expresses their needs related to the system, defining the Expected Behaviour of the system and, directly related, the Systems Functions. On the other hand, the stakeholders defines the first generic requirements, interface requirements and impose constraints, related for example to the current regulation affecting the system. In some complex contests the distinction between customer and stakeholders may not be as clear as it might seem. Here we define Customer as the subject that express the information needed to define the system behaviour, the system mission and the related system functions. The stakeholders are those expressing requirements and constraints basing on the operating context (operating environment, loads, regulator, safety, physical and functional interfaces, etc.). The needs from stakeholders may be not clearly defined from the first design stages and could provide changes during the design development independently from the customers' needs.

The distinction between Customer Needs (CNs) and Stakeholders Needs (SNs) results useful in clearly defining the system mission and then for the traceability and change impact management. In this context we consider CNs the statements defining system main design driver and implementing functions, while SNs specify the constrains and operational domain boundaries. System functions usually do not change during the design activities, while the functional and technical requirements are likely to be frequently updated, especially when the system under design is not yet a "well known" system and the technological feasibility shall be checked, as in the case study discussed in Chapter 4. At this level the system functions are known but there is not yet a set of defined requirements. To start the process a joint working session between sector experts, customers and stakeholders is performed in order to collect few generic needs. The main goals are to understand what are the needs, what is missing, what is sought, what is needed to proceed with design and to find out the technologies to be involved.

There are several methodologies to gather customer needs, such as Quality Function Deployment (QFD) (Sakao 2007) and House of Quality (Hauser and Clausing 1988). The use of IDEFO diagram, as presented in section 2.4.1, can help in collecting CNs and SNs, defining the main system's functions and at the same time providing a first hierarchical structure to CNs, SNs and the related systems functions. Each team could select the most appropriate technique, what is really important is that each customer and stakeholder need is such to be documented and traceable, reporting the statements, the source, the date of elicitation and any related comment discussed during the brainstorming session. Since the activity of needs elicitation should be performed centrally, at system level, and then in the various team involved for each sub-system, templates should be used to improve the communication and ensure that all the information are effectively shared among the project teams. This would ensure also that all those aspects that are not directly related to the design development, such as maintenance needs, reliability and training, are correctly considered from the early stage from all the actors involved, so to develop from the beginning a system compatible with all the needs. A template is provided in Table 5.

Table 5: Template for CNs and SNs collection

System/ sub-system name				
Customer Needs (CNs)				
Id	Statement	Source	Date	Comments
CN1	CN1 description			
CN2	……………			
Stakeholders Needs (SNs)				
SN1	…..	…	…	…

According with Kossiakoff et al.(Kossiakoff *et al.* 2011), we can name this phase a "need analysis phase". The output of this phase is a description of the capabilities and operational effectiveness needed in the new system. In many ways, this description is the first iteration of the system itself, albeit a very basic conceptual model of the system. Although we would not yet call this description a set of requirements, they certainly are the forerunner of what will be defined as official requirements. Some communities refer to this early description as an initial capability description.

2) I level SMART requirements definition

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. While the letters S and M usually indicate specific and measurable respectively, there is not a common criteria to define the other three letters. In this work the suggested interpretation is that the letters A, R and T indicate respectively *achievable, relevant* and *traceable*. These five aspects allow to formulate an effective requirement without misleading. However, unconstrained use of Natural Language (NL) is inherently unsuitable for requirements definition for a number of reasons. Some of the problems that can appear in NL requirement documents are (Rolls-Royce):

- Ambiguity (a word or phrase has two or more different meanings)
- Vagueness (lack of precision, structure and/or detail)
- Complexity (compound requirements containing complex sub-clauses and/or several interrelated statements)
- Omission (missing requirements, particularly requirements to handle unwanted behaviour)
- Duplication (repetition of requirements that are defining the same need)
- Wordiness (use of an unnecessary number of words)
- Inappropriate implementation (statements of how the system should be built, rather than what it should do)
- Untestability (requirements that cannot be proven true or false when the system is implemented)

If requirements are not modelled accurately enough, misunderstanding can arise and be propagated in the different phases of the design processes. Five major types of linguistic ambiguities can be identified (Christophe *et al.* 2014):

- Lexical ambiguity occurs when a word has several meanings
- Syntactic ambiguity occurs when a given sequence of words can be given more than one grammatical structure, and each has a different meaning
- Semantic ambiguity occurs when a sentence has more than one way of reading it within its context even if it contains no lexical or structural ambiguity
- Generality and vagueness occurs when in a sentence boundaries cannot fixed
- Pragmatic ambiguity occurs when a sentence has several meanings in the context in which it is stated.

Identification of the subject (actor or a system name) is necessary in the writing requirements. Three types of requirements are identified in this research:

- *Behaviour - Performance requirement*. This type of requirement is used to indicate the behaviour or a performance that the system must own in the case of a system or in the case of actor the behaviour that the actor shall perform.
- *Design Constraints*. This type of requirement must be used when there are some design constraints that the system must respect.
- *Process Compliance*. This type of requirement must be used when the system of interest is developed or built in accordance with some ISO or more in general other document.

The suggested template for Behaviour Performance Requirement, in the case of system name, is the following:

The <System name> must <behaviour> if <condition>, where <quality factor>.

Upon <conditions>, the <System name> must <behaviour> where <quality factor>.

The standard model for Design Constraints is the following

The <System name> must have <instance> with this <feature>, and/or <constraint>.

The standard model for Process Compliance is the following

The <System name> shall be <programmatic process> in accordance with <document> where <quality factor>.

A SMART requirement often is coupled with the Rationale, that identifies the "why" the requirements is needed and what assumption were made.

Whenever the requirements are written as SMART, they must be assess with two important processes: requirements validation and requirements verification. Requirements validation is the processes of confirming the completeness, compatibility and correctness of the requirements. Requirements verification provides the basis for the qualification of a design and for acceptance of a product. It allows establishing confidence that the requirement has been met. Generally the Project Teams should create a preliminary verification plan to indicate the method (test, demonstration, analysis or/and inspection) that will be used for verifying a requirement.

Figure 20 shows the approach adopted to collect customer and stakeholders' needs and transform them into SMART requirements, while Figure 21 details the needed steps to write SMART requirements.

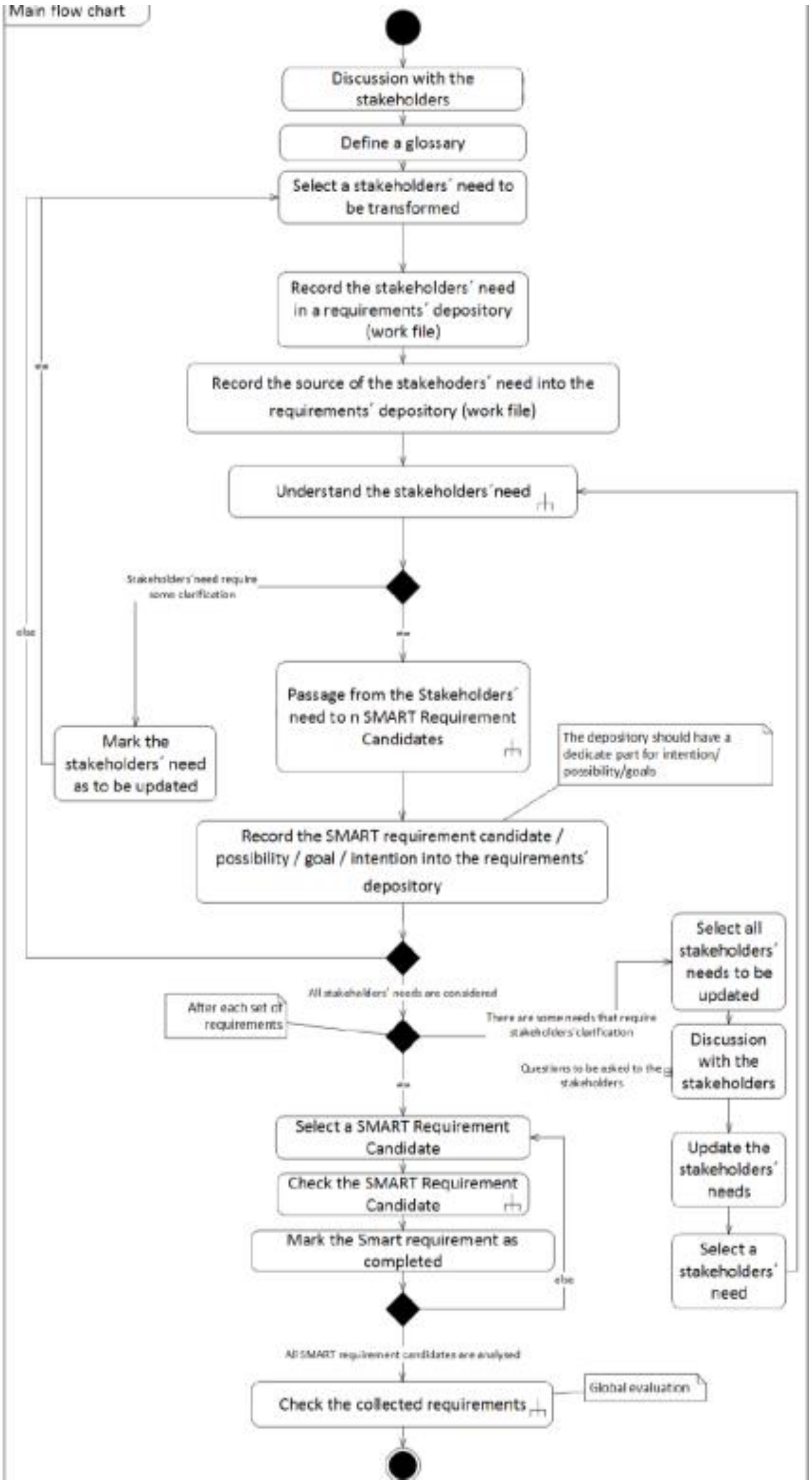


Figure 20. Main flow chart for smart requirements - UML language is used (Rumbaugh, 2004).

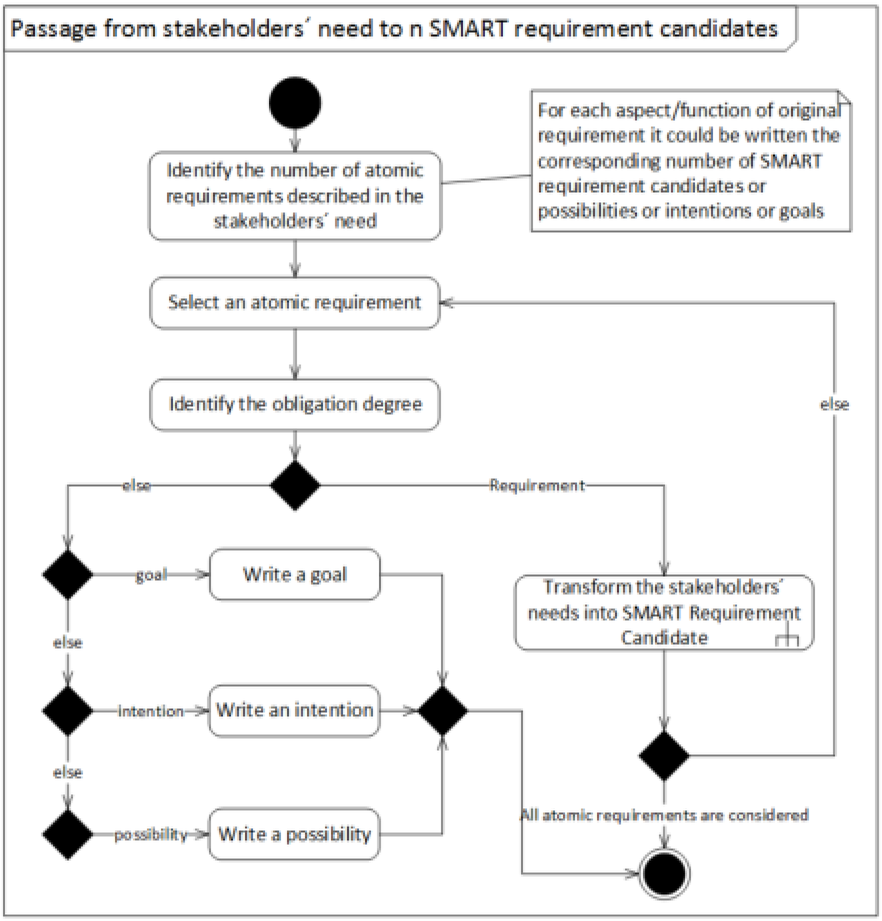


Figure 21. Passage from needs to SMART requirements

The Customer and stakeholders' needs can then be mapped in three types of initial requirement: the initial Functional Requirements (FRs), the Input Constraints (ICs) and the Process Compliance (PCs). 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, ICs and PCs is captured by the equations:

$$\begin{Bmatrix} CN \\ SN \end{Bmatrix} = [R]FR\} \tag{1}$$

$$\begin{Bmatrix} CN \\ SN \end{Bmatrix} = [C]IC\} \tag{2}$$

$$\begin{Bmatrix} CN \\ SN \end{Bmatrix} = [P]PC\} \tag{3}$$

The template proposed for CN/SN mapping is show in Table 6.

Table 6: Template for mapping of FRs/ICs/PCs in CNs and SNs

System/ sub-system name						
FRi ID	FRi description	CN/SN			Type	Verification
		CN1	CN2	SN1		
FRi1	…………….	…	…	….	P/C	……..
FRi2	………….	…	….	…	….	…….
ICi ID	ICi description					
ICi1	………………..	….	…..	…..	……	…….
…..	……………	…	…	….	…..	…….
PCi ID	PCi description					
PCi1	………………	…	…..	…	….	……..
…..	………………	…	…..	..	…..	………

For each defined requirement the verification method is also indicated, to aloe for an easy verification process after design solutions development.

3) *Design solutions development*

Once CNs are mapped to FRs, ICs and PCs, 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 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 (equations (4) and (5)). Also system Structure matrix to DP-SC mapping is developed.

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

$$(5)\qquad \begin{Bmatrix} FR1 \\ FR2 \\ FR3 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ X & 0 & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \end{Bmatrix}$$

The proposed template is shown in Table 7. For each proposed design parameter the Research Units involved in the design are indicated and the DP type is defined.

Table 7. Template for Design Paramenters

System/ sub-system name				
ID	FR	DP	DP Type	RUs involved
1	High level functional requirements description	Design parameters to achieve functional requirements	I	……
1.1	Decomposed functional requirement	Design parameter for decomposed functional requirement	II	……
1.2	……….	....	III	……

In addition to the design parameters type proposed by Gumus (Gumus *et al.* 2008), who identified five type of design parameters, from Type I to Type V in Table 8, IPADeP introduce a new Design Parameters Type, named *Interface*. This Type VI identifies the sub-systems and components used as interface between sub-systems. This is fundamental in highly integrated environment, where subsystem providing interface between different system elements are widely used, and their identification from the beginning can help in interface and requirements change management.

Table 8: DPs type

DP type	Description
Type I (System)	This type of DP describes the system itself, e.g., car, organization, software application, etc. There should be only one DP, the system DP, of this type in the decomposition.
Type II (Conceptual)	This type of DPs describes an abstract/conceptual solution or a design solution that is provided by multiple subsystems. If a DP is determined to be of Type II, it should be decomposed further to Type III, Type IV or Type V DPs.
Type III (Subsystem)	This type of DPs describes a solution that is provided by a subsystem of the proposed system.
Type IV	This type of DPs describes a solution that is provided by an individual

(Component)	component of a subsystem.
Type V (Attribute)	This type of DPs describes a solution that is provided by an attribute(s) of a component(s).
Type VI (Interface)	*This type of DPs identifies the subsystems and components used as interfaces to integrate the subsystems or components.*

4) Development of CAD model and first level analyses

After definition and documentation of DPs of alternative concepts, the development of high level CAD solution and verification analyses represents a crucial stage for communication among design teams and for understanding, from the early stage, of concepts problems, feasibility issues, individuation of possible interfaces and to check that the concepts and design parameters are being developed in the right direction in order to meet the requirements. For these reasons the representations in virtual reality of design concepts, as well as the use of appropriate techniques for CAD modelling allowing parameters optimizations, represents crucial step towards the definition of suitable/ best conceptual solution and to avoid late re-design cycles.
The definition of a conceptual model for small structural elements, as well as for large assemblies, is a step-by-step path that starts from a sketch and ends with a preliminary assessment of different possible design solutions. The complexity of large projects, such as the DEMO reactor considered in this research, obliges to use computer-aided applications for both modelling and structural assessments. In particular, the correct set-up of the CAD environment and adoption of proper modelling methodologies are very important points to consider when approaching a new project, especially during a conceptual design phase, when changes to CAD models are likely to be very frequent. In other words, the digital model has to be easy to maintain and to be changed. Moreover, it would be better if the CAD environment could keep a strong connection (so-called associativity) with FEM analysis environment, even after major CAD changes. In this way, the same load and the same boundary conditions can be applied to different variants, without have to rebuild the entire FEM simulation model. It is clear that this potentially allows saving a considerable amount of time.

As mentioned, the conceptual design phase is an iterative creation process aimed at developing different concepts that potentially meet the “mission need”, but have yet to be further analysed and evaluated (Di Gironimo *et al.* 2015b). In this phase, more than in the others, major changes occur constantly, thus a tight link between CAD and FEA models is crucial to speed-up the whole design process (Armstrong 1994) (De Martino *et al.* 1998). Currently, there are two main approaches to generate computer-aided concepts: CAD-centric and FEM-centric (Gordon 2001, Lee 2005). The first approach is widely adopted: the main design activity is conducted on CAD systems where the concepts are improved and refined time by time through an iterative process involving periodic design review and consequent geometrical changes. Unfortunately, CAD models are often unsuitable for FEA needs (Lee 2005), and therefore an idealization process, involving details suppression as well as geometrical adaptations, is necessary. Moreover also other simulation codes, such as MCNP used for complex facilities like the ITER, rely on their own geometry description and the data conversion need external tools (Weinhorst *et al.* 2015). This means that, whenever a change occurs, the CAD to “simulation environment” adaptation must be carried out again. In a FEM-centric process (Rozov *et al.* 2005), idealized models are used as actual design concepts before developing a reference CAD model. This approach is used especially in a conceptual design stage, but it makes it more difficult to implement major geometrical design modifications. In any case, both approaches require to maintain two different models for the same product, with consequent wasting of time and efforts. Modern CAE systems, like CATIA V5, do provide integrated FEM tools inside the same CAD modelling platform, but these integrated tools mostly do not have the same functionalities as standalone FEA systems and thus cannot be suitable for complex designs that involve different physical aspects (e.g. non-linear effects, electro-magnetic interactions, dynamic effects, elastoplastic models, etc.). Therefore, several authors are focusing on the down-stream connection between CAD models and FE analysis tools. Most of their approaches are based on neutral exchange data formats (STEP, XLM, etc.) that yet cause an “interruption” between the CAD model and FEM model. Other authors are addressing CAD-CAE integration. In particular, Lee (Lee 2005) proposed an integrated approach that involved a multi-abstraction non-manifold topological

(NMT) modelling system. According to this methodology, for each modelling operation, multiple geometric features would be embedded into a single NMT master model. In other words, different types of geometric entities (the ones suitable for design, the other ones for analysis) would be concurrently created and modified. Then, the needed CAD or CAE model would be "extracted" as and when required. However, this approach has some evident limits highlighted by the author himself and in facts does not help the creation of concept variants. Regardless, modern CAD systems, do not implement such a multi-abstraction modelling core, even though NMT modelling is fully integrated in most of them, being especially used in conceptual design phases. Thus, in this research IPADeP does not keep insisting on CAD-CAE integration, but instead focuses on a design methodology that uses the already-available functionalities of modern CAD/CAE tools, such as CATIA V5 and ANSYS, to simplify variants generation during the conceptual design phase and also to keep associativity between CAD and CAE environments.

More specifically, IPADeP propose a CAD-centric design approach improved with a proper Parametric Associative (PA) model.

A PA model is a computer-based description of a geometrical model that depends on non-geometrical entities, the design parameters(Salehi and McMahon 2009). Parametric systems solve constraints by applying sequentially assignments to model variants (Shah and Rogers 1993). Moreover, any parameter-related modification can be automatically propagated to down-stream applications and geometries, keeping the relationship among geometrical objects and features in diverse design process steps (Salehi and McMahon 2009). In particular, ANSYS provides a direct interface with the most common CAD systems that help to keep data consistence with the geometrical models even after design changes. Moreover CAD parameters can be recognized and changed inside the same CAE environment, without have to re-build the reference model.

But, to take advantage of these characteristics, greater attention should be paid on how a PA master model has to be structured and handled to be efficiently linked with FEM environments.

The development of a master model concept for a large assembly should follow the design workflow shown in Figure 22

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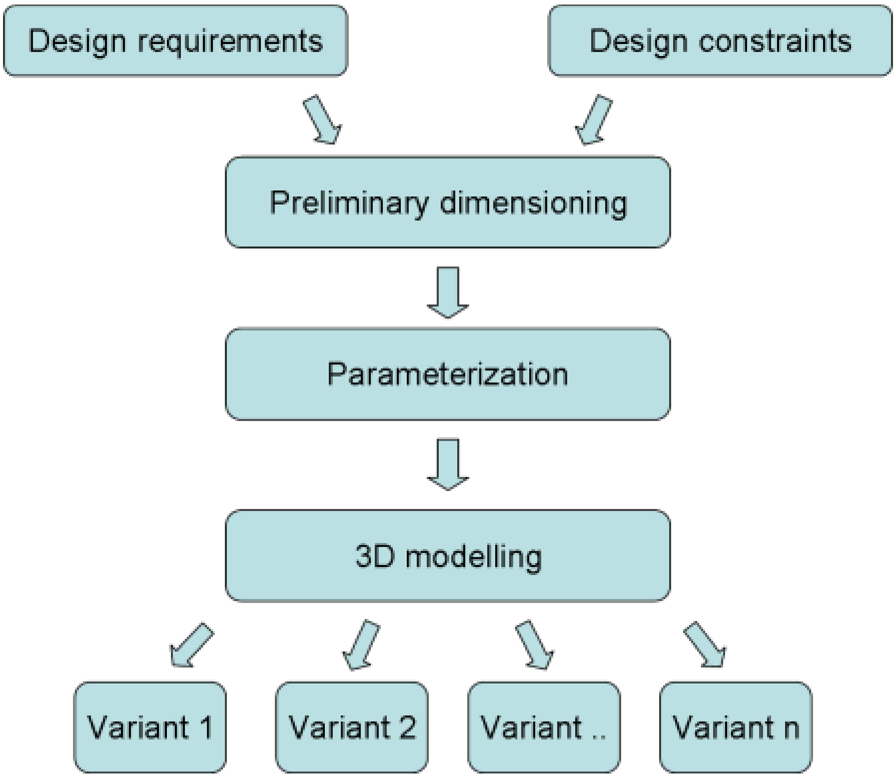


Figure 22: Development of master model concept

Such a workflow is made of several phases:

- Collection of the design requirements, given from FRs/ICs/PCs provided by the different design team involved in sub-system design and its interfacing systems (loads, applicable standards, materials, temperatures, etc.)
- Identification of the main design constraints (overall dimensions, cost, interference issues, maintainability, main technological aspects, etc.) given from FRs/ICs/PCs provided by the different design team involved in sub-system design and its interfacing systems
- Preliminary dimensioning of DPs and SCs.
- Identification of the main design parameters allowing optimization process (e.g. thickness of plates, distance between structural ribs, etc.)
- Development of a parametric 3D master model for each solution
- Generation of geometrical variants for later assessments (structural as well as cost analyses, technological feasibility studies, etc.)

In particular, the identification of a properly small set of parameters driving the 3D geometry (namely, dimensions or properties that are most likely to be changed during the design process) is a key point, especially in a conceptual design stage. The definition of DPs matrix and their mapping in FRs helps in such identification, clearly showing the design parameters characterizing the system and which requirement can be optimized in developing a proper DP. A well-conceived parametric model can indeed be updated by changing a small set of values/properties rather than by deleting existing geometries and creating new ones. In this context, the term "parametric" has a broad sense, because Boolean parameters can be also used to switch among different configurations belonging to the same master model (Lanzotti *et al.* 2009). Parametric 3D models already have well-known advantages over other conceptual 3D sketching techniques (Di Gironimo *et al.* 2012) but here it is worth emphasizing that this methodology also improves the associativity between CAD and FEM models, even when a design variant implies significant changes in terms of shapes and layout.

5) Concept evaluation

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 (Sebastian and Ledoux 2009). 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 (Murat Albayrakoglu 1996, Di Gironimo *et al.* 2013). Since decision makers’ requirements may contain ambiguity and the human judgment on quality attributes may be imprecise (Renzi *et al.* 2013), 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 (Chang 1996, Fu *et al.* 2008, Chen and Wang 2009)

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 phases. 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)?"

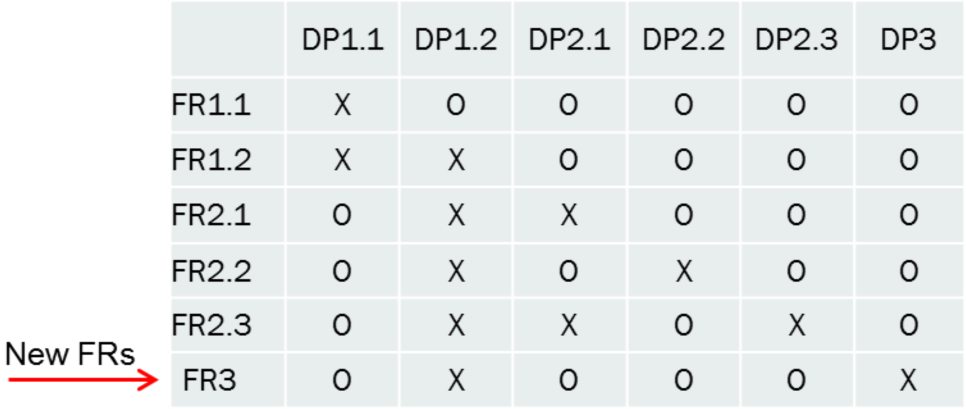
The second stage concerns the weighting of the alternative design options. A second questionnaire is submitted to a different team of experts, asking to pairwise compare the alternatives with respect of each criterion by questions like: "How good is the Alt.i when it is compared to Alt.j as regard the 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 (Chang 1996) to achieve the weights of each solution and identify the best solution.

3.1.2.2 Subsequent iterations

Proceeding with the iterations, when enough information is 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 9) is exploited to check whether the design still respects the independence axiom or the early design decision is violated.

Table 9. Master Design Matrix



New FRs

	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
FR2.3	O	X	X	O	X	O
FR3	O	X	O	O	O	X

As shown in the example of Table 9, a new FR (FR3) introduces a new DP (DP3) but can be also affected by a design parameter previously defined (DP1.2).

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.

4 IPADEP application to tokamak sub-systems

The need to develop the IPADeP method come out from the necessity to deal with the conceptual design stage of a complex system with an high level of uncertainty, the DEMOnstration fusion power plant (DEMO).

Several issues characterize the design development of such a system, first of all coming from the fact that this is an innovative, unknown technology, so no previous experiences are eligible as starting point.

The activities presented in this chapter were developed in close collaboration with Eurofusion Programme Management Unit - Max-Planck-Institut für Plasmaphysik in Garching, Germany (Germany), VTT Technical Research Centre in TAMPERE (Finland), ENEA Research Centre of Frascati (Italy) and ENEA research centre of Brasimone (Italy). IPADeP was assumed as design methodology to deal with the conceptual design of DEMO sub-systems and to provide an efficient tool for the collaboration of the distributed design team.

4.1 Overview on the Demonstration Fusion Power Reactor DEMO

A Tokamak (Russian acronym for toroidalnaya kamera i magnitnaya katiushka, “toroidal chamber and magnetic coil") is a fusion device that uses strong magnetic fields to confine the plasma within a vacuum vessel with a toroidal shape. The first Tokamaks were first developed in the former Soviet Union in the 60s.

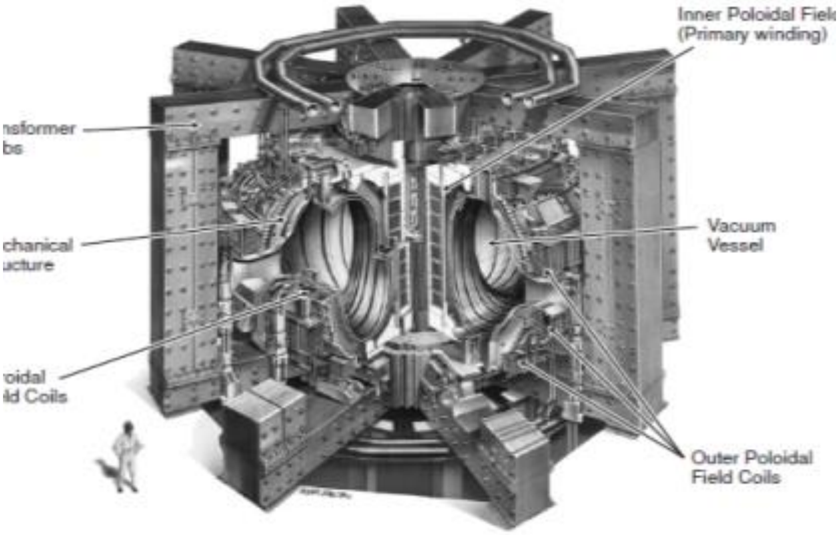


Figure 23. Tokamak Structure

In Tokamaks the plasma is confined in a vacuum vessel (or chamber) by means of a set of toroidal field (TF) coils, while poloidal field (PF) coils permit a precise shaping and positioning of the plasma, as well as the induction of a current in the plasma via transformer effect (central solenoid), and the stabilization of vertical instabilities in case of elongated plasmas. In Figure 23 the standard structure of a Tokamak device is reported. Plasma “border" is usually considered coincident with the LCMS (Last Closed Magnetic Surface), i.e. the last magnetic surface which doesn't intersect any physical object (in case of limiter configuration), or on which lies the X-point for a divertor configuration (separatrix). In Figure 24 the differences between a limiter and a divertor plasma are shown.

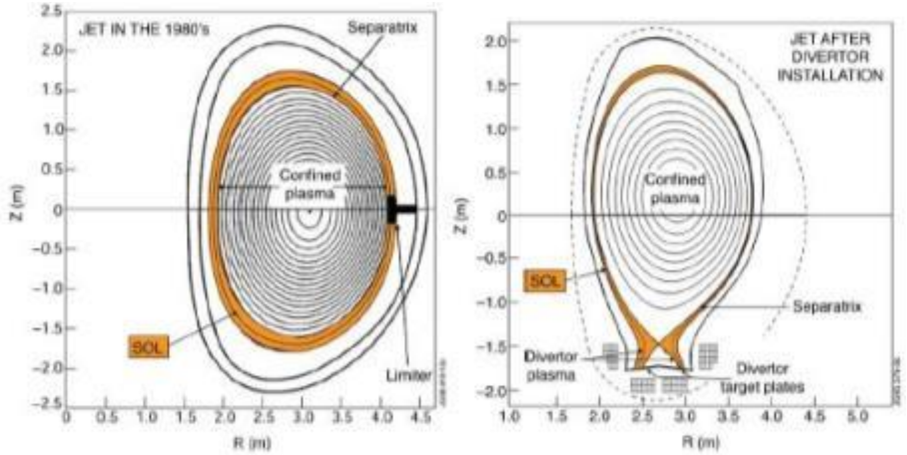


Figure 24. Limiter and diverter plasma configurations

One of the major advantages of the divertor configuration plasmas is the mitigation of the sputtering or melting of material from the limiters to inside the plasma, as impurities in the plasma tend to dilute the fuel and generate radiation losses. Moreover it has been shown that the presence of an X-point greatly helps in reaching high confinement modes (H-mode), thus improving fusion performances (Pironti and Walker 2005). The divertor, which represented the key component in the case studies illustrated below, is one of the most technically challenging components of any tokamak, since it is a plasma-facing component, directly facing the thermonuclear plasma.

One important objective of the EU fusion roadmap Horizon 2020 is to lay the foundation of a Demonstration Fusion Power Reactor (DEMO), with the capability of generating several 100 MW of net electricity to the grid and operating with a closed fuel-cycle by 2050. This is currently viewed by many of the nations engaged in the construction of the International Thermonuclear Experimental Reactor (ITER) (Crisanti *et al.* 2011) as the remaining crucial step towards the exploitation of fusion power.

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

To help in considering all the loads and the impacts of the several interfaces, a context diagram of the whole DEMO fusion power plant was developed, showed in Figure 25. One exceptionally useful function of the Context Diagram is that it implicitly defines the system boundary and thereby communicates it to the system designers, stakeholders and project management. This aids the system integration process, where it is important that all interfaces are identified and managed to avoid confusion or absence of responsibility for components or functions within a system.

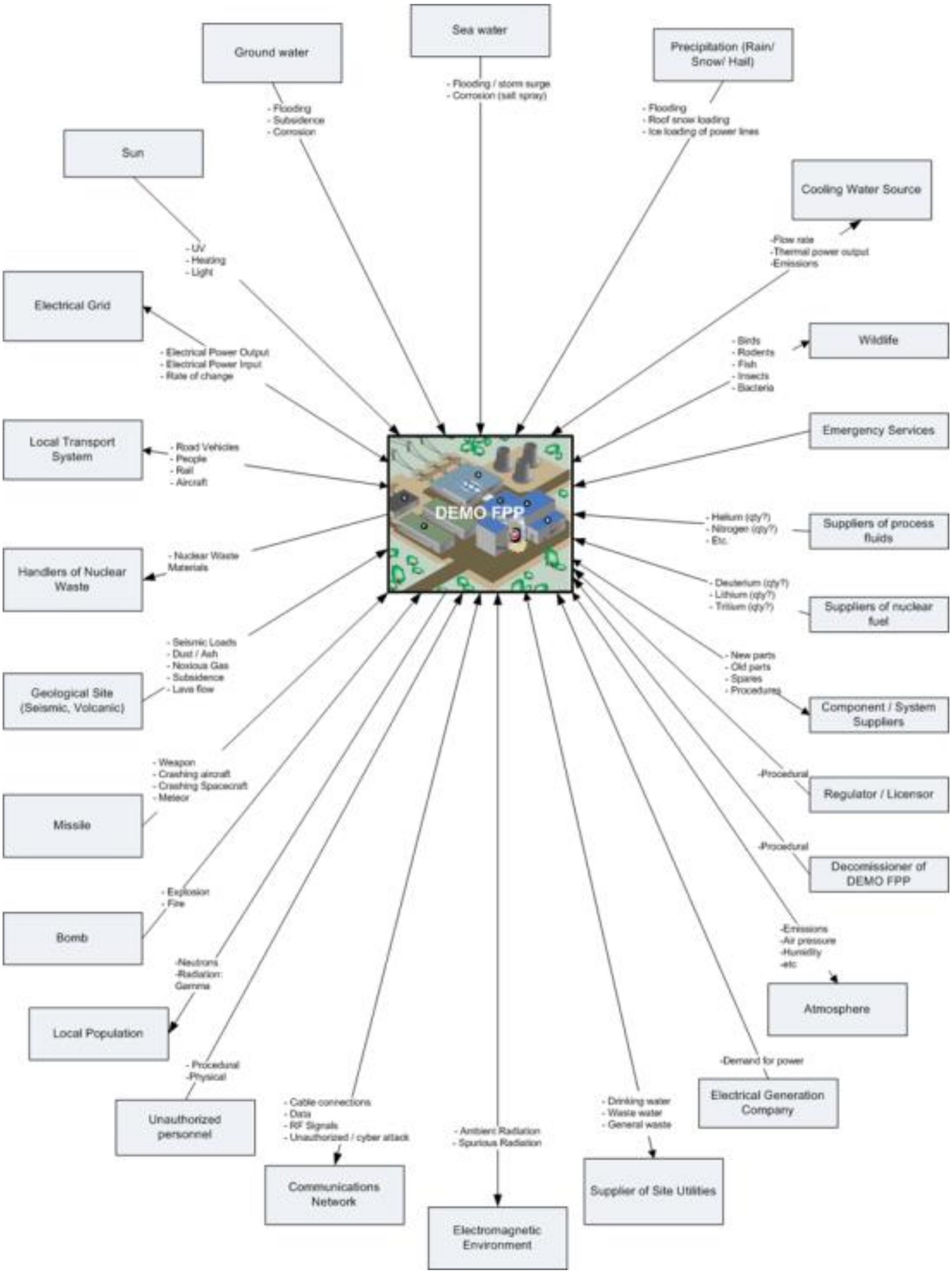


Figure 25. DEMO context diagram [adapted from EUROfusion SE handbook]

4.2 Configuration Management of the EU DEMO conceptual design data

IPADeP highlights the need to define first of all a configuration management system to effectively deal with the conceptual design data management and to optimize the collaboration of the distributed design teams. The EUROfusion Consortium is setting up – as part of the EU Fusion Roadmap – the framework for the implementation of the (pre)conceptual design phase of the DEMO reactor. Configuration management needs have been identified as one of the key elements of this framework, in particular the configuration of the CAD design data. Developing the conceptual design of a fusion power plant is challenging due to its size and complexity but also the large number of interrelated and conflicting requirements that must be balanced between physics, operation, maintenance, safety, availability and cost. A thorough systems engineering and configuration management (Chassignet 1989) approach is vital to ensure the optimum balance between these requirements is achieved. Configuration management of CAD data is a vast topic. The activities performed in this field aimed to cover some of the basic aspects including: (i) the selection of an appropriate Product Data Management (PDM) tool; (ii) the definition of the configuration management philosophy proposed for DEMO CAD design data; and (iii) the key enablers of the design configuration management process. The conflicting requirements of creating a robust system whilst also maintaining a light-weight and manageable approach were traded off.

4.2.1 Selecting the product data management tool

The selection of a product data management tool appropriate for managing CAD data is essential. The PDM tool facilitates configuration management and therefore careful consideration in its selection is required. Given the extensive sole use of the Dassault Systèmes CATIA design tool within the European nuclear fusion community, for general design purposes, establishes the need for good CATIA integration within the PDM tool. Based on this requirement a pre-selection of three potentially suitable tools was undertaken; Dassault SMARTEAM, Dassault ENOVIA V5 and Das-sault ENOVIA V6 were selected. Other independent tools were also considered (e.g. ORACLE AGILE) but have been eliminated due to less established CATIA integration and limited user base within the fusion community. The evaluation of the selected tools was developed according to the systems engineering approach described in this research: from a discussion with the potential customers and stakeholders, identified in the research units involved in the DEMO project, a set of needs has been collected, from which some high level evaluation criteria were established. Table 10 reports the evaluation criteria with the importance weighting corresponding to numbers according to the Fuzzy Analytical Hierarchy Process (F-AHP). The pair-wise comparison reduced the selection down to two tools, SMARTEAM and ENOVIA V6 each with similar scores. As such, a further evaluation of the two systems was required (Meszaros *et al.* 2016).

Table 10. Evaluation Criteria for DEMO CAD management system

Evaluation Criteria	Importance/ weight
Easy access to contributing RUs, access control	High
Safe central CAD data storage	High
Document numbering-automatic allocation of part number	Medium
Long term perspective (upgrade after the CDA phase)	Low
Simultaneous engineering possibility	Medium
Low CAD management time	Low
Recording and retrieving of CAD document hierarchical stuctures	Medium
Version control	High
Ability to manage products configuration variants	Medium
Multiple design option management	High
Product development phase management (e.g. pre-concept, concept, scheme, etc….)	Low
BOM management (for costing/weight analysis/procurement & manufacturing)	Low
Standard Part and Off Shelf (COTS) parts management	Low
Multi-site access	Medium
Web Access	High
Multi-CAD storage	Low
Expertise at Rus	High
Acceptance of the choice	High
Search Functionality	Medium

Using ITER as a benchmark with current experience of implementing an ENOVIA PDM system requiring direct access by all research units highlighted the complexity of establishing such a system (Chiocchio *et al.* 2007). It was agreed, that a more light-weight PDM solution was required for the early phases of DEMO, a statement strongly supported by an Expert Group, established to advice PPPT. As such a recommendation was adopted for the implementation of a PDM tool limited for use locally by the PMU mainly for the version control, interface management and variants/ options management of the design data. Nevertheless it would support exchange of data through IDM (ITER Document Management), the document management system of the Eurofusion consortium. The result would be a simplified interface for all the research units. The new requirements were as follows:

- Robust knowledge of the chosen tool must be available in the fusion community to be provided to the PMU.
- Low infrastructure management time requirement (easy to administer and handle due to the limited resources of the PMU).
- Tool must be easy to configure ‘out of the box’ with options for simple in house customizations if required.

As a result of the new requirements SMARTEAM was selected as the preferred choice. Some clear advantages being

- High level of expertise and competence in implementation and use of SmarTeam for CAD configuration management within the fusion community including Culham Centre for Fusion Energy and Fusion for Energy Broader Approach department in Garching.
- Open database access allowing easy customizing and manipulation of the data for enhanced functionality and /or reporting purposes.

It has been noted that Dassault plans to limit its effort on the future development of SMARTEAM in preference for its new PDM systems. Therefore the future potential of SMARTEAM may be somewhat limited, however migration of the data to ENOVIA V6 or similar system is possible, if required.

4.2.2 Configuration management philosophy for DEMO CAD design data

One of the key benefits of configuration management is access to the right data at the right time. Often version control is confused with configuration management. Whilst it is important to version control, configuration management deals with accessing the correct data and subsequently the correct version of that data. In the conceptual design phase many options to a solution may exist, i.e. multiple CAD data sets each with various version states. This makes configuration management essential in order to support the design process. Figure 26 shows an overview of how the CAD data is configured within the product structure. This structure is replicated in the SMARTEAM PDM tool and is the methodology used to implement configuration management.

The Plant Breakdown Structure (PBS) is the tree structure off which design data is hung. It represents and manages the hierarchical parent-child relationship of the plant, e.g. the Toroidal field coil under the Magnet systems in the tree. The PBS in this instance is broken down by system starting with DEMO at the top and the cascading system and sub-system hierarchy structured below.

The Configuration Item (CI) is the lowest level of assembly within the PBS tree. It represents the point at which change management and version control are implemented. The advantage of such a system is that the Configuration Manager has the ability to select the appropriate configuration level during the various development phases, e.g. for the conceptual development this level could be set at the toroidal field coil system or the vacuum vessel system. Once the design matures the configuration level could be reallocated further down at sub-assembly level, e.g. toroidal field coil casing.

The Link Item (LI) is the link between the PBS tree and the CAD data that hangs off it. The LI acts as the switch that allows the turning on and off ‘configuration’ of options and attribute filtering.

The Design Solution (DS) is the unique container, which holds the CAD data. The same CAD data may be used in many DS instances. The DS is the highest level object in the design data structure subject to change management and version control.

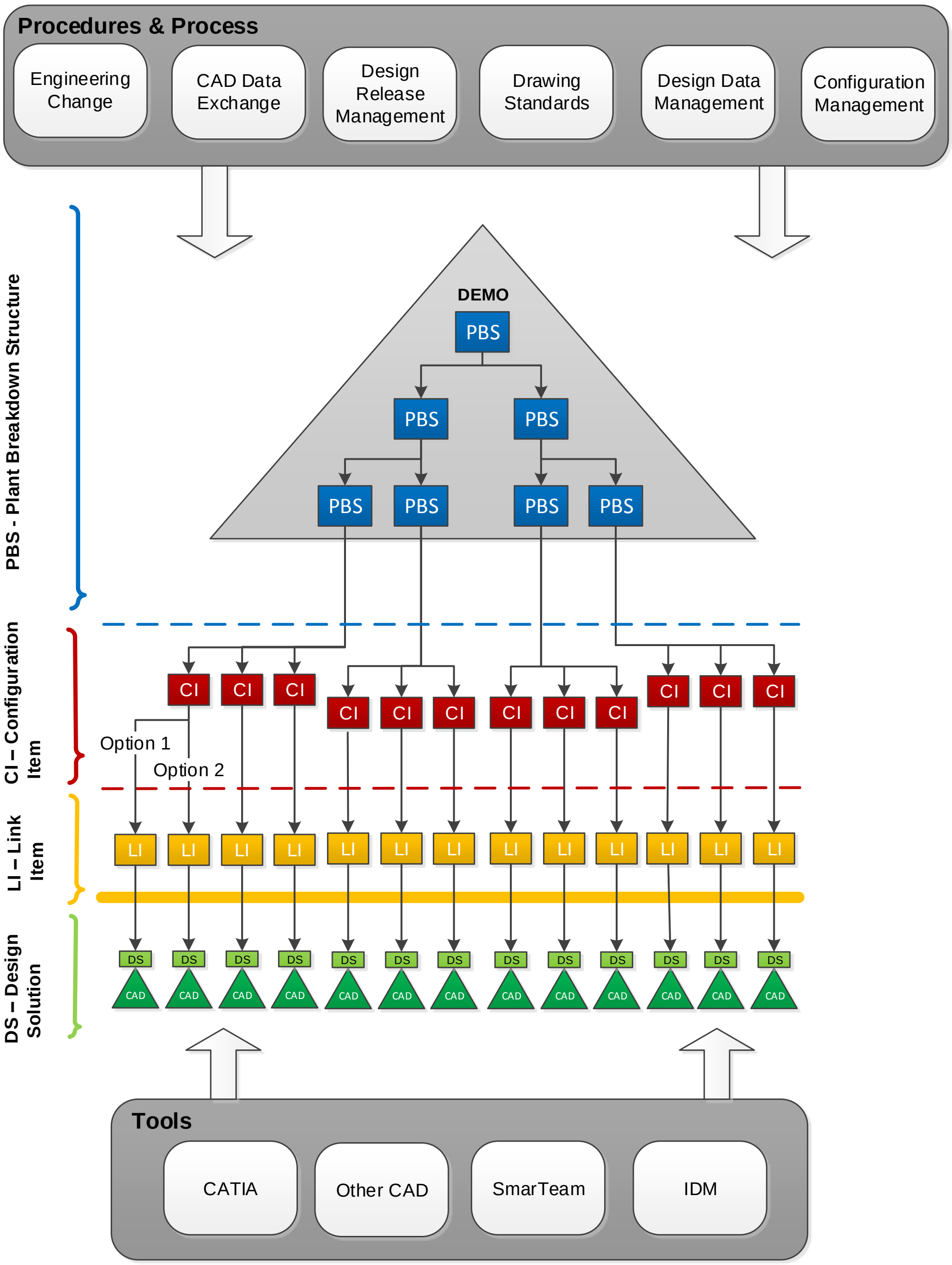


Figure 26. Visualization of the configuration management philosophy

The items layers of PBS, CI and LI allow configuration management of the CAD data below. The layers are managed and represented through items in the SMARTEAM database. The yellow line in Figure 26 is an important boundary between the items and the design data objects. Using this item centric approach allows the simple manipulation of the tree structure and product attributes without affecting the CAD data. In essence, this establishes configuration as a management process as defined in ISO 10007:2003 standard and not a design process which it can often be mistaken for.

Configuration management facilitates many functionalities such as baselining, alternate (option) management, status accounting and electronic bill of material generation. However, one of the most important aspects of configuration management is change management. It is one, if not the main, focal point of product development. Change management can be considered as any change to the configuration and must be underpinned by a robust process.

The described approach results in the CAD data structure being wide and flat (Figure 27). The hierarchy of the product is established through the configuration (items management).

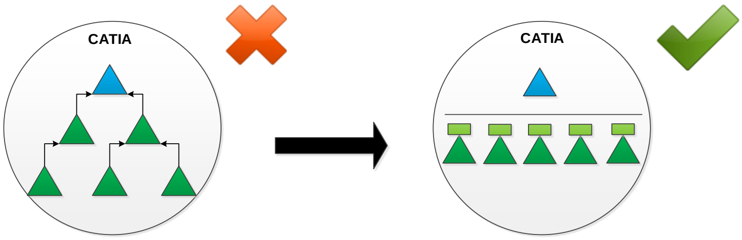


Figure 27. Moving from a hierarchical CAD product to a wide and flat structure

A common mistake is to build this product hierarchy within the CAD design environment making change management and configuration management virtually impossible. Left to their own devices CAD designers would naturally create large hierarchical assemblies within the CAD design environment. The result is that change of a lower level assembly cascades all the way up the tree requiring up-issue of all impacted assemblies. This makes change management overly cumbersome and inefficient. Additionally without a defined plant breakdown structure the designer is required to select where the top of the assembly tree should end. In theory they could choose the very top level DEMO PBS or anywhere in between, further complicating configuration and change management.

Taking the CAD hierarchy shown on the left of Figure 27 and applying configuration management with a PBS structure one can generate a Digital Mock Up (DMU) of the DEMO design to rapidly visualize the large amount of data (Figure 27 right). DMU is primarily a tool for product visualization and geometric analysis; the data is an approximation of the native CAD and is how substantial performance benefits are won. Since the DMU is generated off the configured PBS the LIs will always point to the correct CAD data with which to generate the DMU. This means the DMU can be filtered and regenerated on the fly to look at options or different baselines by simply filtering through the attributes carried by the LI switches. This way one always looks at the correct CAD data at the right time. It is this CI-LI-DS relationship that allows management of the configuration.

4.2.3 Enablers of the configuration management of the design data

There are various enablers of the design configuration management, i.e. appropriate procedures and processes established and tools used. Due to the early stage of the DEMO development and very importantly the strong ties to the global configuration management system yet to be established, such procedures are still under development, except for the following topics described below, which are considered highly important. As for the tools, CATIA, SMARTEAM and IDM are selected to play a key role in the design configuration management.

As mentioned above, one of the most important enabler of such a system is a robust change management procedure. Engineering change is the process of systematically reviewing all modifications to a configured baseline to ensure that the impact of changes on performance, cost and schedule are identified and the change classification is identified before implementation. Engineering change is therefore required to introduce, remove or modify existing items in the baseline. There is currently a Design Change Request (DCR) procedure in place for the DEMO development, which is designed to accommodate the limited available resources whilst providing as much functionality of the design change management as possible (Figure 28).

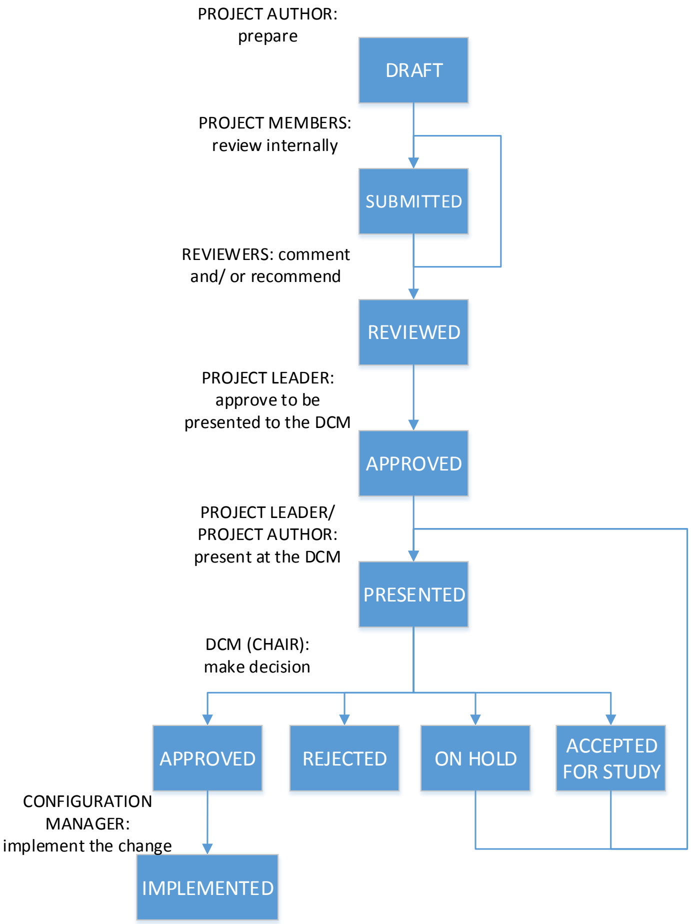


Figure 28. Design Change Request (DCR) procedure.

The DCR procedure is initiated by one of the design groups working on a DEMO system, which generates and internally reviews a DCR before it is submitted to the design authority body called Design Configuration Meeting (DCM) for consideration. The meeting members (the project leaders selected to lead the development of the major DEMO systems) are steered to an agreement by the meeting chair, and make one of the following decisions for the DCR: i) approval; ii) rejection; iii) acceptance for further study in the event vital information relevant to the decision is lacking; or iv) on hold, due to concerns regarding maturity or possibility to obtain the necessary information. Finally, at the end of the procedure, the configuration manager is responsible for the actual implementation of the proposed change in case of approval.

Since the SMARTEAM system is installed for the DEMO integration and used only locally by the PMU, a way for CAD data exchange had to be established. One of the main criteria for selecting a data exchange system was the familiarity of all the contributors with the system. This resulted in the document management system of the Eurofusion consortium (IDM) being used for this purpose. The engineering section of IDM is in any case developed to host analysis data files, plant break-down structure and other technical information, so the programming effort invested in the code to allow the storage and therefore the exchange of CAD data was rather low. Contributors are asked to compress all the relevant files and upload them to a pre-structured area of IDM/engineering. As usual, a unique ID number is assigned to each model along with the following: title, model number, designer name (co-designers/contributors), date, link to related IDM documents, link to previous version, CAD model file and a brief description.

Having defined the CAD configuration management model, this research activities was focused in applying IPADeP for developing the conceptual design of two main DEMO sub-systems, directly interfacing: the divertor and the vacuum vessel.

4.3 Concept design of DEMO divertor

4.3.1 Customer needs and stakeholders needs identification

The first step in the conceptual design of DEMO divertor was the identification of customer and stakeholders and the collection of their needs. To correctly identify all the customers and stakeholders, first it is useful to identify and capture the system functions. The functions try to capture in abstract way the behaviour of the system without specifying the physical implementation (technology, etc.) of systems performing them. Function architecture tree considers four category of functions:

- Process function: proper system mission functions fulfilling the main system driver
- Enabling function
- System Protection functions
- Nuclear Safety functions

Functional behaviour was further described by means of IDEFØ diagrams [IDEFØ] (up to level two) produced on the base of system function tree, in order to represent function interactions, controls and mechanisms. IDEFØ are hierarchical (i.e. diagrams structures are exploded to provide further details on sub-functions) and use blocks as basic units with arrows identifying:

- INPUT: arrows entering left side of the box represent items that trigger the function/activity
- OUTPUT: arrows exiting right side of the box represent the results of performing the activity/function
- CONTROLS: arrows entering upper side of the box imply a guide or regulatory effect on the function
- MECHANISMS: arrows entering upper side of the box represent systems/equipment/people performing/implementing the activity

For each considered system also the following was defined:

- SYSTEM_STATES outlines the foreseen system states as derived from DEMO foreseen operational states
- Context and interfaces: the list of physical- functional interfaces to other DEMO systems foreseen for the considered system. For Divertor also a summary diagram of main physical phenomena characterizing the coupling between Divertor Plasma Facing Components and Plasma itself is provided.
- SYSTEM_PBS provides the high level component breakdown design configuration
- Requirements provides a collection of requirement statements as derived from available system SRD.

From the discussion with the relevant customer and stakeholders, it was agreed that DEMO divertor system mission can be summarized in the following statement: “[..] The divertor system mission is to exhaust the scrape-off layer (SOL) power, which arrives at the divertor target plates by plasma conduction and convection (particles) or by radiation (photons and neutral particles) from the divertor plasma volume. It must realize this function while maintaining acceptable core plasma impurity (both due to helium ash produced by fusion reactions and impurities released as a consequence of the plasma–surface interaction)[..]. [..] as the main interface component between the plasma and material surfaces, the divertor must tolerate high heat loads while at the same time providing neutron shielding for the Vacuum Vessel and magnet coils in its vicinity in reactor level device like ITER.”

Divertor is a key component for modern tokamak concepts, located within vacuum vessel, whose mission is to exhaust plasma ashes while controlling plasma pollution. Despite the fact that a single null configuration with divertor located at the bottom of Toroidal plasma chamber is commonly adopted (e.g. ITER concept) other configurations are also proposed so that the provided analysis is kept implementation-free whenever possible.

Figure 29 provides a context diagram for the Divertor system and shows the main divertor interfaces and control systems

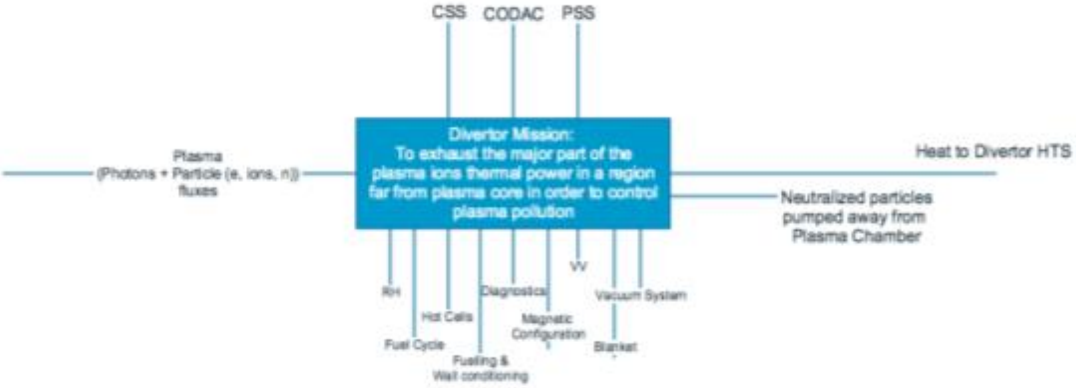


Figure 29. Divertor system context diagram

The interface with plasma system is characterized by a wide variety of phenomena mainly characterized in terms of particle and energy exchange balance between divertor plasma facing components and plasma itself. The interface with plasma system results in performance/loads withstanding requirements for the divertor system. The Figure 30 and Figure 31 show the main interfaces on the divertor

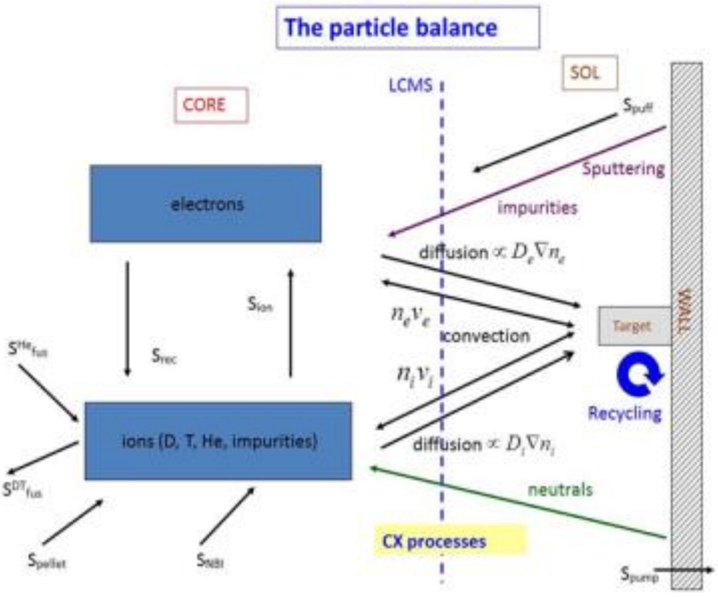


Figure 30. Particle Balance on divertor

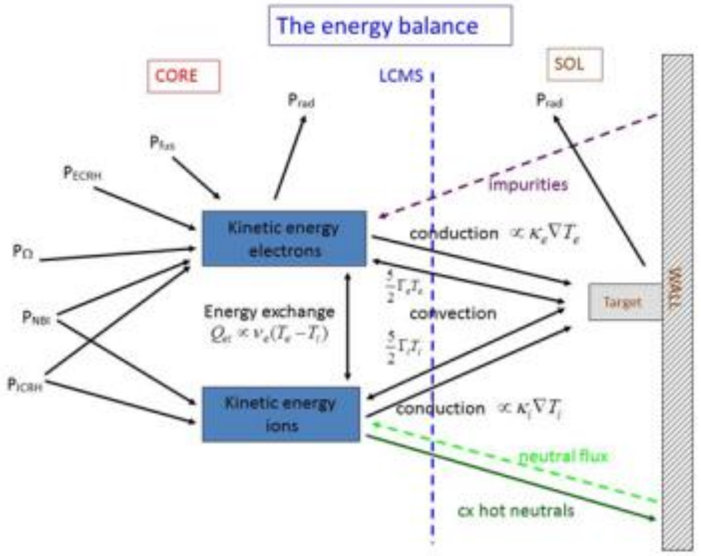


Figure 31. Energy Balance on divertor

Moving from the stated system mission a functional analysis was performed in order to make explicit in a hierarchical structure all the functions the divertor system shall implement to fulfill the reported system mission. System function tree was developed together with divertor physics expert taking into account the main ITER reference documents.

Some behavioral diagrams in the IDEFØ formats were developed for the main functions in a hierarchical form. Enabling mechanisms enter from the bottom the function boxes (see for details on IDEFØ). The main functions are further developed in Figure 32.

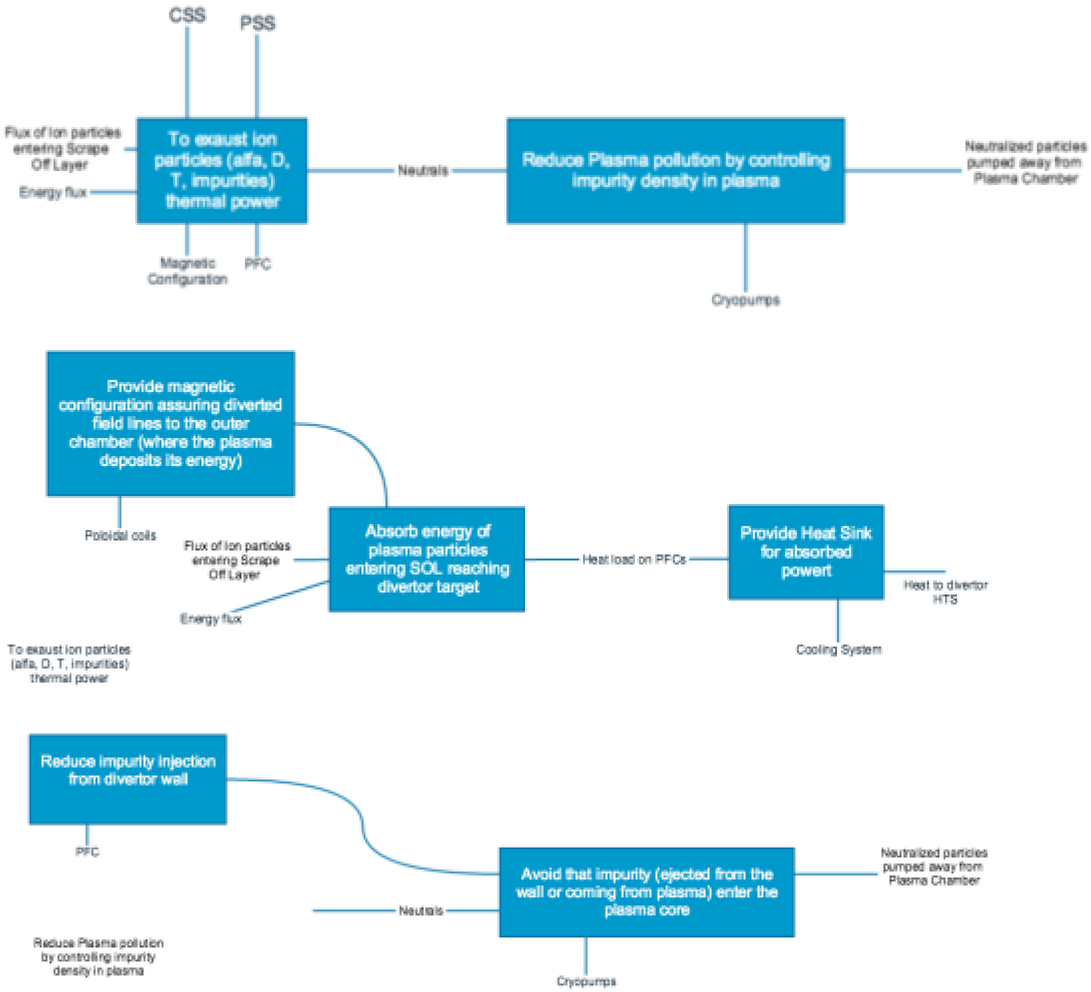


Figure 32. IDEFO diagram decomposition

Having defined the main divertor functions, the system' s customer and stakeholders, with all the possible interfaces, have been clearly identified. Two main divertor sub-system have been identified to be first developed:

1) Divertor cassette-to-Vacuum Vessel fixation system
2) Plasma Facing Component cooling system and its integration of cassette body

Given its high dependences from/to critical interfacing systems (i.e. Vacuum Vessel, Remote Maintenance System, etc.) the main focus of the first conceptual design activities was the divertor fixation system.

As regards this sub-system, several considerations come out from the brainstorming sessions with the identified customer and stakeholders. The main statements are collected in Table 11 (Di Gironimo *et al.* 2015a).

Table 11. Early assumptions

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

After the first needs and assumptions were gathered , according with Axiomatic Product Development Lifecycle few first Customer and Stakeholders Needs with an high level of abstraction were extrapolated, and collected in the template proposed for IPADeP application. The first CNs needs are related to the main functions of the divertor fixation system, while the SNs are related to the main technical requirements and constraints (Table 12).

Table 12. Divertor CNs and SNs

Divertor CB-to-VV fixation system				
Customer Needs (CNs)				
Id	Statement	Source	Date	Comments
CN1	Lock divertor in place after placement operations, avoid displacement in any load conditions.	Brainstorming session – VTT-CCFE-ENEA-PMU	07/2014	
CN2	Maximize reactor availability using systems with short maintenance time and avoid unplanned stop.	Brainstorming session – VTT-CCFE-ENEA-PMU	07/2014	Consider from the beginning the Remote Maintenance compatibility
Stakeholders Needs (SNs)				
SN1	Avoid "shaking" due to sudden change of magnetic field	Brainstorming session – VTT-CCFE-ENEA-PMU	07/2014	

The distinction between CNs and SNs results useful in clearly define the system mission and then for the traceability and change impact management. In this context we consider CNs the statements defining system main driver and implementing functions, while SNs specify the constrains and operational domain boundaries. System functions usually do not change during the design activities, while the functional and technical requirements are likely to be frequently updated, especially when the system under design is not yet a "well known" system and the technological feasibility shall be checked, as the case under study.

4.3.2 First level SMART requirements definition

The Customer Needs (CNs) and the Stakeholder Needs (SNs) were analysed and few "high level" initial Functional Requirements (FRis) and Input Constraints (ICis) were derived, according to the SMART requirements definition flowchart (Figure 20). As discussed earlier, the mapping and the design matrix are fundamental for the traceability of the design activities and to easily evaluate the impact of requirements change during the design development. FRis and ICis are collected in Table 13, mapped to CNs and SNs. For each FRi and ICi the type and the verification method is defined, according to the IPADeP definition presented in 3.1.2.1. In Italics are the definition needed to complete the initial general requirements and achieve a SMART requirement.

Table 13. FRi and ICi mapping

Divertor CB-to-VV fixation system – I level requirements						
FRi ID	FRi description	CN/SN			Type	Verification
		CN1	CN2	SN1		
FRi1	Remove clearances to avoid vibrations – *clearances of maximum 5 mm*	0	X	0	P/C	VR simulations
FRi2	Provide an outer locking system able to take force in any direction – *ITER-like loads to be considered*	X	0	0	P	Structural Simulations
ICi ID	ICi 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	C	VR simulations
ICi1.2	*As simple as possible* mechanism to lock and preload in order to reduce operational time	X	X	X	C/P	VR simulations
ICi1.3	Locking System shall be the same for all standard cassette (left and right)	X	X	X	C	CAD check
ICi1.4	Structural robust locking system – *withstand ITER-like extraordinary events*	X	X	X	P/C	Structural simulations

For all the loads and interfaces assumed from ITER, the reference documents are reported in Table 14. All the documents are available in the IDM.

Table 14. ITER reference documents

ITER PBS	ITER ICD	DEMO PBS	System description	Physical-Functional Interface
15	ITER_D_2WC5RM	D1-TC-01-02, D1-TC-01-01-04	Vacuum Vessel, ELM Coils and Manifolds	P - F
16	ITER_D_2KTFAD	D1-TC-01-03	Blanket System	P - F
18	ITER_D_2KTM5B		Fuelling and Wall Conditioning System	P - F
22	ITER_D_2M5XA2	D1-TC-07	Machine Assembly and Tooling	P - F
23	ITER_D_2LXG42	D1-TC-06	Remote Handling System	P - F
26	ITER_D_2LVGK3	D1-TC-03	Cooling Water System	P - F
31	ITER_D_2MSPPM		Vacuum System	P - F
32	ITER_D_2MPAMC		Tritium Plant	F
43	ITER_D_2M58YP		Steady-State Electric Power Supply Networks	P - F
44	ITER_D_33GQW3		Cable Trays System	P - F
45	ITER_D_2V3VPR		CODAC	P - F
46	ITER_D_2LX2D9		Central Interlock System	P - F

47	ITER_D_6VVZ9J		Plasma Control System	P - F
55	ITER_D_2N2DJV		Diagnostics	P - F
62-11	ITER_D_2E485J		Tokamak Building	P - F
62-74	ITER_D_2E485J		Diagnostic Building	P - F
62-21	ITER_D_2EPQ6T		Hot Cell Building	P - F
66	ITER_D_2KUMD3		Radioactive Waste Treatment and Storage	P - F
98-TS	ITER_D_34N7Z3		Transportation	P - F
	ITER_D_2LKTW5		Interface with Plasma	P - F

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

4.3.3 Alternative design solution definition

As the elicitation of needs and assumption also in this stage brainstorming sessions was carried out, during which for each functional requirements some alternative design parameters and system components was proposed by fusion experts.

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

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

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

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

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

The decomposition start from this FR/DP/SC triplet. Once the parent FR and DP as well as the allocated ICs to the parent DP are given, the functions that the DP has to perform in order to achieve the parent FR and satisfy the allocated ICs are determined and they are listed as the children FRs. The decomposition and zigzagging continues by finding or developing DPs for the newly established FRs, Table 15.

Table 15. Fixation system first level DPs

Divertor CB-to-VV fixation system				
ID	**FR**	**DP**	**DP Type**	**RUs involved**
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	ENEA
1.1	Remove any clearances to avoid vibration	Cassette preloading	II	ENEA/VTT
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	ENEA

The corresponding design matrix showed that the DPs are acceptable basing on Independence Axiom (Equation 4.1).

$$\begin{Bmatrix} FR1.1 \\ FR1.2 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP1.1 \\ DP1.2 \end{Bmatrix} \qquad (4.1)$$

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

Table 16. DPs- ICs mapping

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

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

According with zigzagging principles Table 17 and Table 19show the decomposition level 1.

Table 17. Decomposition level 1 for DP 1.1

Divertor CB-to-VV fixation system			
ID	**FR**	**DP**	**DP Type**
1.1	Remove any clearances to avoid vibrations	Cassette preloading	II
1.1.1	Cassette preloading	(a) Insert tool to preload cassette (b)Preload cassette taking advantage of the mass of cassette	III

To meet functional requirements 1.1.1 two alternative design parameters were proposed during brainstorming session. Both are shown in Table 17. For next decomposition both were considered separately, the decomposition proceed in parallel, thus reaching at the end of decomposition in different solutions.

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

Table 18. DP1.1 SCs

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

As regard the system components, different proposals were suggested during brainstorming sessions, each one is reported in Table 18and results in a single solution.

Table 19 and Table 20 show the decomposition and system components for FR/DP 1.2.

Table 19. Decomposition for DP1.2

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

Table 20. DP1.2 SCs

Divertor CB-to-VV fixation system				
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

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

$$\begin{Bmatrix} FR1.1.1 \\ FR1.2.1 \\ FR1.2.2 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ X & 0 & X \end{bmatrix} \begin{Bmatrix} \mathrm{DP1.1.1(a)} \\ \mathrm{DP1.2.1(a)(b)} \\ \mathrm{DP1.2.2} \end{Bmatrix} \qquad (4.2)$$

$$\begin{Bmatrix} FR1.1.1 \\ FR1.2.1 \\ FR1.2.2 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP1.1.1(b) \\ DP1.2.1(a)(b) \\ DP1.2.2 \end{Bmatrix} \qquad (4.3)$$

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

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

4.3.3.1 CAD design in CATIA V5

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

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

According to what discussed in section 3.1.2.1, CAD-centric design approach was adopted with a proper Parametric Associative (PA) model, linked to FEM environment in order to allow optimization analyses and the easy adaptation to changing design requirements.

Each of the solutions presented below have been modeled assuming parameters for the main geometric dimensions, which could be involved in optimization analyses and could be affected by requirements changes.

The first solution generated during brainstorming sessions is shown in Figure 33

Figure 33. First concept for fixation system

The concept idea was to preload the cassette pushing in a tool with a spherical surface. 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 preload and the relative displacement of 5mm. All the degrees of freedom are locked by the socket engagements formed on cassette and supports.

The basic principles of the operations are:

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

The idea underneath the second concept was to taking advantage of the mass of cassette using a gear arrangement to preload cassette, and then insert an “I” shaped tool able to withstand vertical and radial loads. The solution is shown in Figure 34

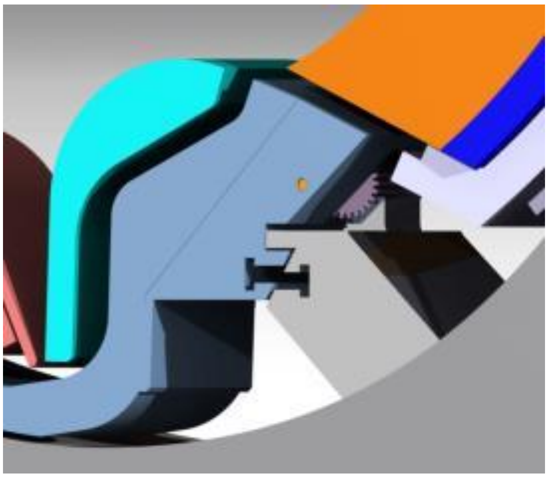


Figure 34. Second concept for cassette fixation

The basic principles of the operations are:

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

As well as in the solution II also in third solution is exploited the mass of the divertor, using a "cam" arrangement instead of the gear ones. The principle of operation is the same as the previous solution, Figure 35.

Figure 35. Third concept for cassette fixation

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

4.3.4 Preliminary verification

According to the verification methods listed in Table 13, FEM and Virtual Reality analyses were carried on for each solution as a support to evaluation phase, to better understand the load distribution and as a more objective ways to evaluate the structural robustness and the feasibility of the different solutions. A FEM analysis is also a way to refine structural and material requirements, and provide a first idea about the necessary thickness and dimensions to withstand the high loads as extrapolated from ITER load cases.

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

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

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

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

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

Given the conceptual design issues discussed in this research, three main aspects are required to the FEM model at this stage:

- The possibility to propagate design changes from CAD model to FEM model
- The parametric associativity to perform optimization analyses and to easily manage design changes
- The possibility to integrate different analyses coming from several interfacing physics (multi-physics integration) and to update input analyses as they are updated and changed as design mature.

As discussed, the first two point have been implemented through the PA approach in CAD design and the direct link between CATIA V5 parameters and ANSYS Workbench.

AS regard the third point, it was better implemented from the second iteration of the process, as it will be discussed in the following sections, since at first level, characterized from an high level of abstraction, the results from the different interfacing physics were not available. In fact this results could be obtained only basing on a first high level geometry, which must be developed taking into account that some requirements can be defined only if a first model is available. This point is the most critical issue related to the integration of various physics during the first stage of the design, and IPADeP aims to efficiently manage the parallel development of different aspects and the requirements refinement.

For the first iteration ITER-like resultant loads were considered and applied in the FEM model.

The forces were applied transforming them in pressure on surfaces, and moments are applied as two parallel forces in opposite. Figure 36 shows the imported geometry and the loads applied to the three solutions. As regard the post-processing phase, equivalent Von-Mises stress is shown in Figure 37, and the obtained safety factor with reference to equivalent stress is shown in Figure 38. The results are also collected in Table 21.

Table 21. 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

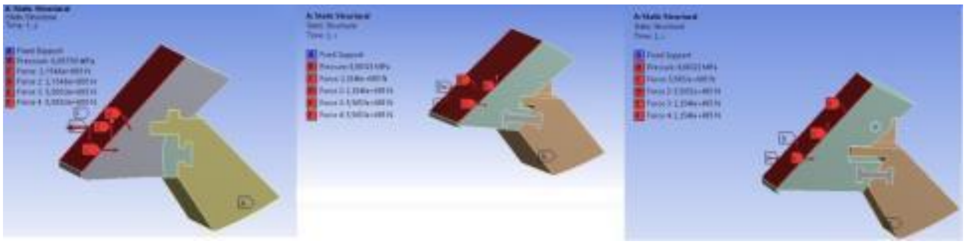


Figure 36. Geometries and loads

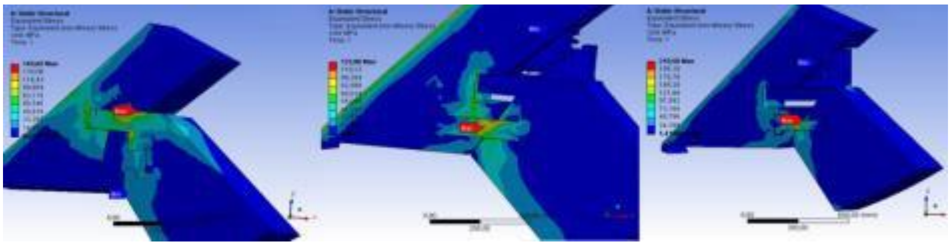


Figure 37. Von- Mises stress

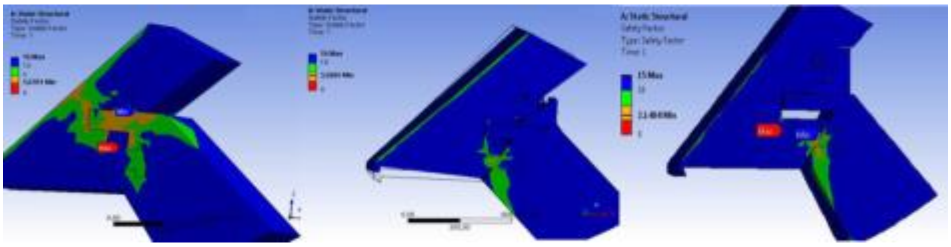


Figure 38. Safety factors

4.3.5 Concept evaluation using Fuzzy-AHP

Concept evaluation was carried out by means of Fuzzy-AHP. Two different team of experts were involved in the evaluation: first, the "DTP-2" team at VTT technical research centre of Finland was asked to fill the first section of the questionnaire. It was the section about the "preference" in which the selected evaluation criteria were pair-wise compared. The chosen criteria are shown in Table 22:

Table 22. Evaluation Criteria

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

Decision makers answer their preference about the criteria using Fuzzy Linguistic Variables shown in Table 23:

Table 23. Fuzzy Linguistic Scale

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

Transforming the results obtained into triangular Fuzzy numbers, getting the average values and applying the extent analysis the weight vector with respect to the decision criteria C1, C2, C3 was obtained (Figure 39):

W= (0.3477; 0.343; 0.309)

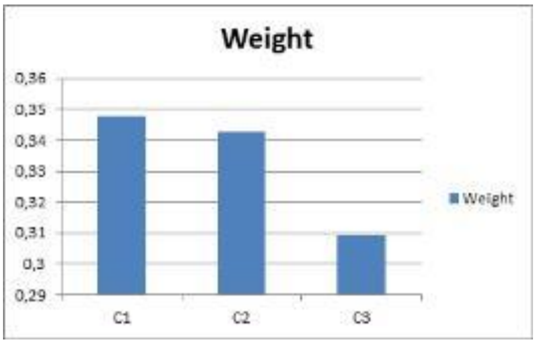


Figure 39. Criteria Weight

Then the pair wise comparison among conceptual alternatives was carried out in IDEAinVR Lab at the University of Naples "Federico II"- Department of Industrial Engineering, where it was asked to a team of engineers to compare the alternatives with respect of each criteria using the fuzzy linguistic variables shown in Table 24:

Table 24. Linguistic Scale

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

The two concepts were shown on two different screens together with the two simulations realized Figure 40.

Figure 40. Pair wise comparison at IDEAinVR lab

Getting the average values of the results obtained by the questionnaire the following Fuzzy evaluation matrices are obtained, Table 25, Table 26 and Table 27:

Table 25. Scores against criterion C1

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

Table 26. Scores against criterion C2

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

Table 27 Scores against criterion C3

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

Then, applying the extent analysis, these matrices are used to estimate weights, in this case weights of each candidate under each criterion separately. The results are given in Table 28 and Figure 41.

Table 28 . Alternatives Score

criterion	A1	A2	A3
C1	0,623	0,225	0,151
C2	0,397	0,312	0,289
C3	0,163	0,398	0,437

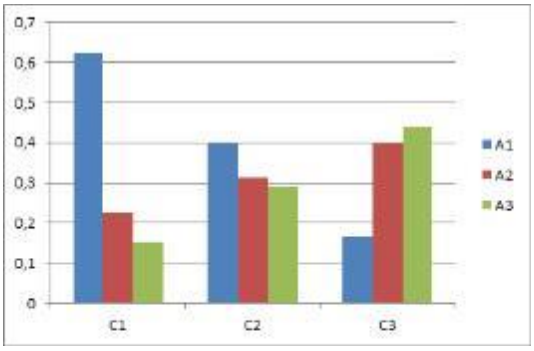


Figure 41. Alternatives score

Finally, adding the weights per candidate multiplied by the weights of the corresponding criteria, a final score is obtained for each candidate. **Table 35** and Figure 42 show these scores:

Table 29. Final score

	A1	A2	A3
Final Scores	0,40382	0,3087	0,2874

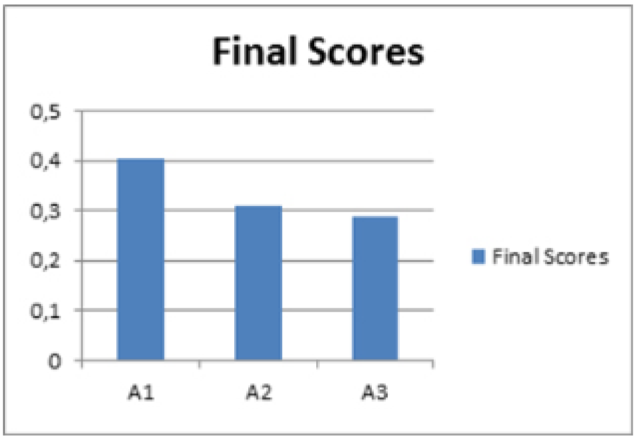


Figure 42. Final Score

According to the final scores, it is clear that Concept I was the preferred alternative. Therefore, the Concept I has been the starting point for the further decomposition and next iterations of IPADeP, that has been characterized by intensive changes and refinements of requirements, as discussed in next sections.

4.3.6 Description of selected solution

At this step, all the documentation related to the design activities should be collected to support the next iterations design process and to correctly share the information with the involved research units. The CAD models of all the solutions analysed were uploaded in SMARTEAM and the selected solution were promoted as reference solution. The documentation has been uploaded in EUROfusion IDM, containing the design description document (DDD) of the fixation system selected , the templates developed in each step and the design matrix to ensure design activities traceability.

4.4 Second iteration

The design proceeded to the second level of the design following IPADeP iteration: the zigzagging and decomposition of higher level FRs and DPs is performed and at the same time new information (overall dimensions, shape, interfaces, etc.) come from the development of interfaced components. In detail, several progresses on DEMO divertor and DEMO Vacuum Vessel were performed, resulting in new interface requirements. Moreover new, updated, CAD configuration models of the Divertor and Vacuum Vessel were released (Figure 48) (Marzullo *et al.* 2015). These models were used as new input for the design. From the new reports published on the interfaced components (Frosi *et al.* 2015, Mazzone and Frosi 2015) new requirements for the locking system were elicited. Table 30 collects the “first level” and “second level” information. The second level information represents substantially more accurate definitions of the previous requirements, or new interface indications coming forth from the development of the interfaced components and from analyses developed basing on the first geometry released during first iteration.

For each information is also indicated, in italics, what is needed in order to allow for the definition of a SMART requirement.

Table 30. Second level informations

First iteration information	**Second iteration information**
General requirements	
Deliver high availability – *"high" to be defined in measurable entity*	
Be flexible to new or changed task requirements	
Deliver High quality operation – *define "High quality" in measurable entity*	
Perform operation safely – *define "safely" in measurable entity*	
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. – *define" rapid" in measurable entity*
	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 – *interface with RH system shall be defined*	
	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. *"Define clearance in measurable entity"*
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
	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. – *define magnitude of distortions*
	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).

A team of experts was involved in the analysis of the new information, which did not result in conflict with higher level assumptions.

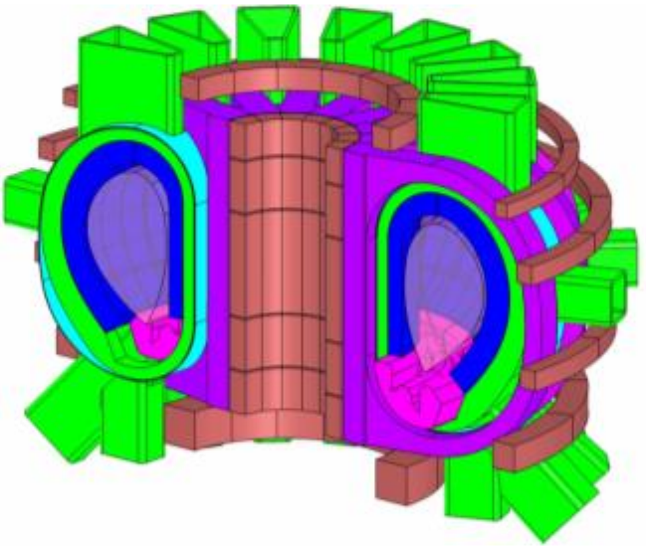


Figure 43. DEMO 2015 Configuration Model

Basing on new requirements, CNs and SNs were re-evaluated and a new SN was added to the previous table (SN2 – Table 31).

Table 31. CNs and SNs for second iteration

Divertor CB-to-VV fixation system				
Customer Needs (CNs)				
Id	Statement	Source	Date	Comments
CN1	Lock divertor in place after placement operations, avoid displacement in any load conditions.	Brainstorming session – VTT-CCFE-ENEA-PMU	07/2014	
CN2	Maximize reactor availability using systems with short maintenance time and avoid unplanned stop.	Brainstorming session – VTT-CCFE-ENEA-PMU	07/2014	Consider from the beginning the Remote Maintenance compatibility
Stakeholders Needs (SNs)				
SN1	Avoid “shaking” due to sudden change of magnetic field	Brainstorming session – VTT-CCFE-ENEA-PMU	07/2014	
SN2	Accommodate distortions	Brainstorming session – VTT-CCFE-ENEA-PMU	05/2015	Fixation system should accommodate thermal distortions to avoid secondary stess in the cassette

The new SN led to new FRs and DPs. Table 32 shows the initial functional requirements (FRis) and Input Constraint (ICs) mapped to CNs and SNs. 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 32. Second level FRs and ICs

Divertor CB-to-VV fixation system – I level requirements							
FRi ID	FRi description	CN/SN				Type	Verification
		CN1	CN2	SN1	SN2		
FRi1	Remove clearances to avoid vibrations – *clearances of maximum 5 mm*	0	X	0	0	P/C	VR simulations
FRi2	Provide an outer locking system able to take force in any direction – *ITER-like loads to be considered*	X	0	0	0	P	Structural Simulations
FRi3	*Provide a system to accommodate themal distortion for a total displacement of 10 mm.*	0	0	0	X	P/C	Structural simulations
ICi ID	ICi 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	C	VR simulations
ICi1.2	*As simple as possible* mechanism to lock and preload in order to reduce operational time	X	X	X	0	C/P	VR simulations
ICi1.3	Locking System shall be the same for all standard cassette (left and right)	X	X	X	X	C	CAD check
ICi1.4	Structural robust locking system – *withstand ITER-like extraordinary events*	X	X	X	X	P/C	Structural simulations
ICi1.5	*Geometry and interface consistent with Divertor CAD model 2014*	X	X	X	X	C	CAD check
ICi1.6	*Dead weight 17.2 ton*	X	X	0	0	C	CAD check

Keeping good documentation and traceability, this kind of approach helps to optimize in any phase the information available, avoiding redesign cycle. Table 33 shows the updated FRs and the DPs up to the second level of decomposition and Figure 44 summarize decomposition and zigzagging process for the FR 1.1.

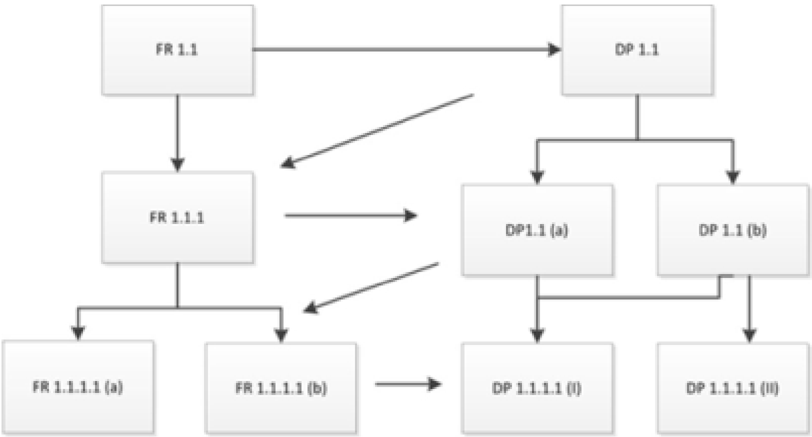


Figure 44. Decomposition and zigzagging

Table 33. Decomposition level 2

Level	ID	FR	DP
0	1.1	Remove any clearances to avoid vibrations – clearance of maximum 5 mm	Cassette preloading of 5 mm
I	1.1.1	Preloading the cassette to obtain 5 mm displacement	(a) Insert tool to preload cassette of 5 mm (b) Preload cassette of 5 mm 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 –ITER-like loads	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, considering ITER-like loads as reference	(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 ITER-like 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 for a total displacement of 10 mm	Allow small rotations around the tangential axis for a total displacement of 10 mm
I	1.3.1	Allow small rotation around the tangential axis for a total displacement of 10 mm	(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.

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

Equations (4.5) and (4.6) show the decoupled Design matrix at level 1. Equations (4.7) and (4.8) show the partially coupled design matrix at the second level.

Design solutions emerging from the decomposition were an improvement of the previous solutions to meet new requirements FRi3 and the input constraint ICi1.5 and ICi1.6.

$$\begin{Bmatrix} \mathrm{FR1.1.1} \\ \mathrm{FR1.2.1} \\ \mathrm{FR1.2.2} \\ \mathrm{FR1.3.1} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ X & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} \mathrm{DP1.1.1(a)} \\ \mathrm{DP1.2.1(a)(b)} \\ \mathrm{DP1.2.2} \\ \mathrm{DP\ 1.3.1(a)(b)} \end{Bmatrix} \tag{4.5}$$

$$\begin{Bmatrix} \mathrm{FR1.1.1} \\ \mathrm{FR1.2.1} \\ \mathrm{FR1.2.2} \\ \mathrm{FR\ 1.3.1} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} \mathrm{DP1.1.1(b)} \\ \mathrm{DP1.2.1(a)(b)} \\ \mathrm{DP1.2.2} \\ \mathrm{DP1.3.1} \end{Bmatrix} \tag{4.6}$$

$$\begin{Bmatrix} \mathrm{FR1.1.1.1\ (b)} \\ \mathrm{FR1.2.1.1(a)} \\ \mathrm{FR1.2.2.1} \\ \mathrm{FR1.3.1.1(b)} \end{Bmatrix} = \begin{bmatrix} X & X & 0 & 0 \\ 0 & X & X & X \\ 0 & 0 & X & X \\ 0 & 0 & X & X \end{bmatrix} \begin{Bmatrix} \mathrm{DP1.1.1.1(I)} \\ \mathrm{DP1.2.1.1(I)} \\ \mathrm{DP1.2.2.1(I)} \\ \mathrm{DP1.3.1.1(II)} \end{Bmatrix} \tag{4.7}$$

$$\begin{Bmatrix} \mathrm{FR1.1.1.1\ (a)} \\ \mathrm{FR1.2.1.1(b)} \\ \mathrm{FR1.2.2.1} \\ \mathrm{FR1.3.1.1(a)} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & X & 0 \\ 0 & X & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} \mathrm{DP1.1.1.1(II)} \\ \mathrm{DP1.2.1.1(II)} \\ \mathrm{DP1.2.2.1(II)} \\ \mathrm{DP1.3.1.1(I)} \end{Bmatrix} \tag{4.8}$$

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. Figure 45 shows the model of this first solution, which integrates 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” (Figure 46) 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.

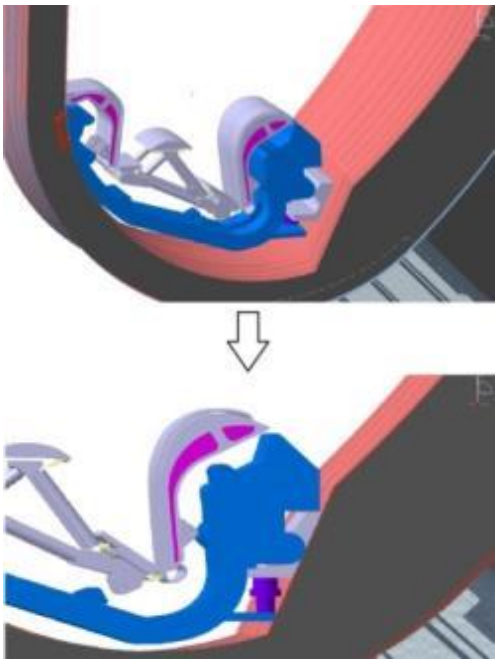


Figure 45. Second level solution A

Figure 46. Second level solution B

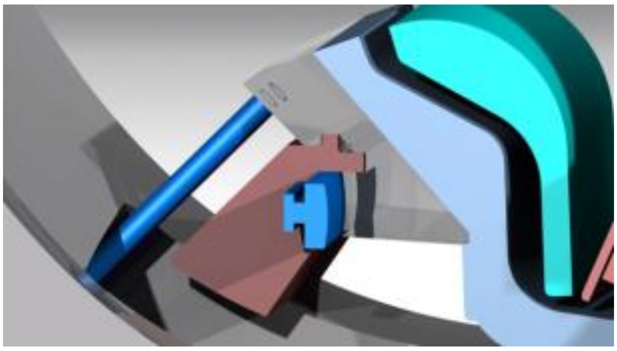


Figure 47. Second level solution C

Kinematic, VR and structural analyses were performed for each solution, in order compare them from the kinematic point of view and verify the solutions proposed against the defined functional requirements. The SMART requirements definition allows design team to verify solutions against measurable requirements from the first stage of the design and enhances the view of the decision makers that can refer to quantitative data. Moving from these inputs the three proposed solutions have been reviewed to allow for 5 mm displacement and accommodate the exact magnitude of distortions. This approach has prevented the premature selection at "high level" of solution possibly not meeting specific measurable requirements, therefore avoiding re-design cycle later during the design process.

As prescribed by IPADeP, the solutions were compared using the Fuzzy- AHP. 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 34.

Table 34. 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 12 engineers members of CREATE consortium, EUROfusion Consortium and ENEA organization, joining 13 master students, 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 (Chang 1996), achieving the final score Table 35.

Table 35. Final scores

	A1 (Fig. 7) (I level concept)	A2 (Fig.10) (II level concept)	A3 (Fig. 11) (cam arrangement)
Final Scores	0.3	0,27	0,45

The "cam arrangement" concept was the preferred solution, and represents the chosen concept design. Tanks to the SMART requirements, the decision makers had a more precise view of the FRs to be addressed, hence putting in evidence the CAM arrangement as better suited in preloading cassette of 5 mm and accommodating distortion for a total displacement of 10 mm.

4.5 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 2015. Differences with divertor 2014 are shown in Figure 48
- 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

Furthermore, basing on the PA FEM model set up during the first and second level design, it has been possible during the third iteration to easily deal with the refined loads requirements (Marzullo *et al.* 2017). Basing on Second level geometry provided in SMARTEAM and IDM, the team working on neutronic and EM calculation were able to provide the loads distribution on divertor cassette body in terms of power density and EM body force density.

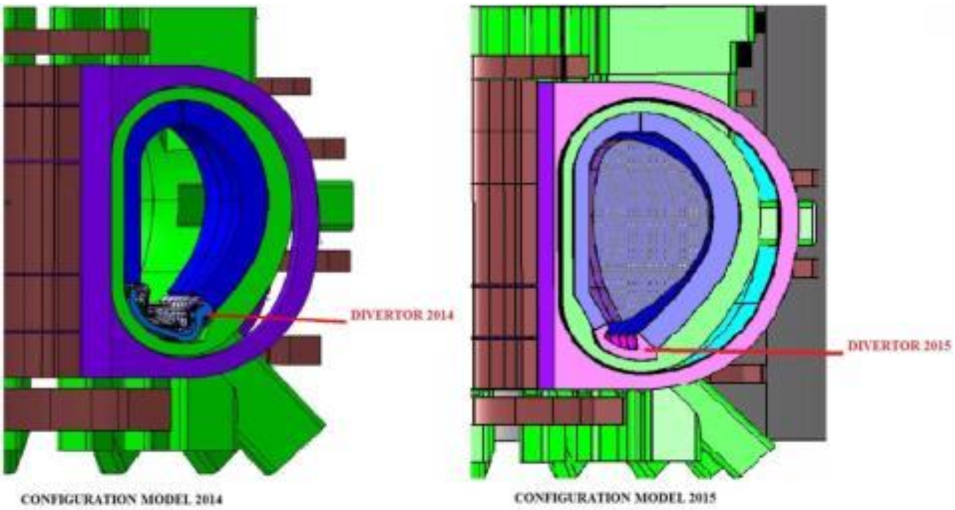


Figure 48. DEMO configuration model for 2016

The first information represents a higher level change. From the mapping tables is easily verifiable that this change affects the input constraint ICi 1.5 (Table 36), and all the design parameters developed during the first iteration can be adopted also with the new constraint. Note that design parameters shall be consistent with the ICi1.5, but they do not depend on it. This implies that, since according to IPADeP the project started from an high level of abstraction, all of 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 36. The updates FRs and ICs are reported in Table 37.

Table 36. Third level CNs and SNs

<table>
<tr><th colspan="5">Divertor CB-to-VV fixation system</th></tr>
<tr><th colspan="5">Customer Needs (CNs)</th></tr>
<tr><th>Id</th><th>Statement</th><th>Source</th><th>Date</th><th>Comments</th></tr>
<tr><td>CN1</td><td>Lock divertor in place after placement operations, avoid displacement in any load conditions.</td><td>Brainstorming session – VTT-CCFE-ENEA-PMU</td><td>07/2014</td><td></td></tr>
<tr><td>CN2</td><td>Maximize reactor availability using systems with short maintenance time and avoid unplanned stop.</td><td>Brainstorming session – VTT-CCFE-ENEA-PMU</td><td>07/2014</td><td>Consider from the beginning the Remote Maintenance compatibility</td></tr>
<tr><th colspan="5">Stakeholders Needs (SNs)</th></tr>
<tr><td>SN1</td><td>Avoid “shaking” due to sudden change of magnetic field</td><td>Brainstorming session – VTT-CCFE-ENEA-PMU</td><td>07/2014</td><td></td></tr>
<tr><td>SN2</td><td>Accommodate distortions</td><td>Brainstorming session – VTT-CCFE-ENEA-PMU</td><td>05/2015</td><td>Fixation system should accommodate thermal distortions to avoid secondary stress in the cassette</td></tr>
<tr><td>SN3</td><td><i>Provide electrical connection between divertor cassette and Vacuum Vessel during operations</i></td><td>Brainstorming session – VTT-CCFE-ENEA-PMU</td><td>03/2016</td><td></td></tr>
<tr><td>SN4</td><td><i>Avoid sliding surfaces</i></td><td>Brainstorming session – VTT-CCFE-ENEA-PMU</td><td>03/2016</td><td></td></tr>
</table>

Table 37. Third level FRs and ICs

Divertor CB-to-VV fixation system – I level requirements									
FRi ID	FRi description	CN/SN						Type	Verification
		CN1	CN2	SN1	SN2	SN3	SN4		
FRi1	Remove clearances to avoid vibrations – *clearances of maximum 5 mm*	0	X	0	0	X	0	P/C	VR simulations
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	P	Structural Simulations
FRi3	*Provide a system to accommodate thermal distortion for a total displacement of 10 mm.*	0	0	0	X	0	X	P/C	Structural simulations
FRi4	*Provide a system to ensure electrical connection during sudden change of magnetic field.*	0	X	0	X	X	0	p	EM simulations
ICi ID	ICi 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	C	VR simulations
ICi1.2	*As simple as possible* mechanism to lock and preload in order to reduce operational time	X	X	X	0	0	X	C/P	VR simulations
ICi1.3	Locking System shall be the same for all standard cassette (left and right)	X	X	X	X	0	0	C	CAD check
ICi1.4	Structural robust locking system – *withstand ITER-like extraordinary events*	X	X	X	X	0	0	P/C	Structural simulations
ICi1.5	*Geometry and interface consistent with Divertor CAD model 2015*	X	X	X	X	0	X	C	CAD check
ICi1.6	*Dead weight 4 ton*	X	X	0	0	0	0	C	CAD check
ICi1.7	*Avoid sliding surfaces*	0	0	0	X	0	X	C	VR simulations

The DP meeting this functional requirements are listed in Table 38, which can be added as additional rows to Table 33.

Table 38. Third iteration: Design Parameters

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.

$$\begin{Bmatrix} FR1.1.1 \\ FR1.2.1 \\ FR1.2.2 \\ FR1.3.1 \\ FR1.4.1 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ X & 0 & X & 0 \\ 0 & 0 & 0 & X \\ X & 0 & X & X \end{bmatrix} \begin{Bmatrix} DP1.1.1(a) \\ DP1.2.1(a)(b) \\ DP1.2.2 \\ DP\ 1.3.1(a)(b) \\ DP\ 1.4.1\ (a)(b) \end{Bmatrix} \tag{4.9}$$

$$\begin{Bmatrix} FR1.1.1.1\ (b) \\ FR1.2.1.1(a) \\ FR1.2.2.1 \\ FR1.3.1.1(b) \\ FR1.4.1.1 \end{Bmatrix} = \begin{bmatrix} X & X & 0 & 0 \\ 0 & X & X & X \\ 0 & 0 & X & X \\ 0 & 0 & X & X \\ X & 0 & X & X \end{bmatrix} \begin{Bmatrix} DP1.1.1.1(I) \\ DP1.2.1.1(I) \\ DP1.2.2.1(I) \\ DP1.3.1.1(II) \\ DP1.4.1.1\ (I) \end{Bmatrix} \tag{4.10}$$

$$\begin{Bmatrix} FR1.1.1.1\ (b) \\ FR1.2.1.1(a) \\ FR1.2.2.1 \\ FR1.3.1.1(b) \\ FR1.4.1.1 \end{Bmatrix} = \begin{bmatrix} X & X & 0 & 0 \\ 0 & X & X & X \\ 0 & 0 & X & X \\ 0 & 0 & X & X \\ 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP1.1.1.1(I) \\ DP1.2.1.1(I) \\ DP1.2.2.1(I) \\ DP1.3.1.1(II) \\ DP1.4.1.1\ (II) \end{Bmatrix} \tag{4.11}$$

$$\begin{Bmatrix} FR1.1.1.1\ (b) \\ FR1.2.1.1(a) \\ FR1.2.2.1 \\ FR1.3.1.1(b) \\ FR1.4.1.1 \end{Bmatrix} = \begin{bmatrix} X & X & 0 & X \\ 0 & X & X & X \\ 0 & 0 & X & X \\ 0 & 0 & X & X \\ 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP1.1.1.1(I) \\ DP1.2.1.1(I) \\ DP1.2.2.1(I) \\ DP1.3.1.1(II) \\ DP1.4.1.1\ (III) \end{Bmatrix} \tag{4.12}$$

As showed in matrix (4.10) the option to ensure the connection by preloading the cassette generates an uncoupled design matrix. In this case three actions can be taken: 1) modify the lower level DPs, 2) impose constraints or specify conditions that prevent the DPs unwanted effects, or 3) revise the higher level design matrix provided that the revised design matrix is still uncoupled or decoupled. According to the second action, here we can assert that the DPs providing to preload cassette is able to meet both the gap closure and the electrical connection functional requirements. Since these two functional requirements are closely linked, i.e. if the gap is closed not only shaking is avoided but also electrical connection is ensured, we can consider also this design as acceptable, since the DPs do not present unwanted effects.

Basing on the new DPs and ICs, design of higher level solutions have 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 Figure 49. 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.

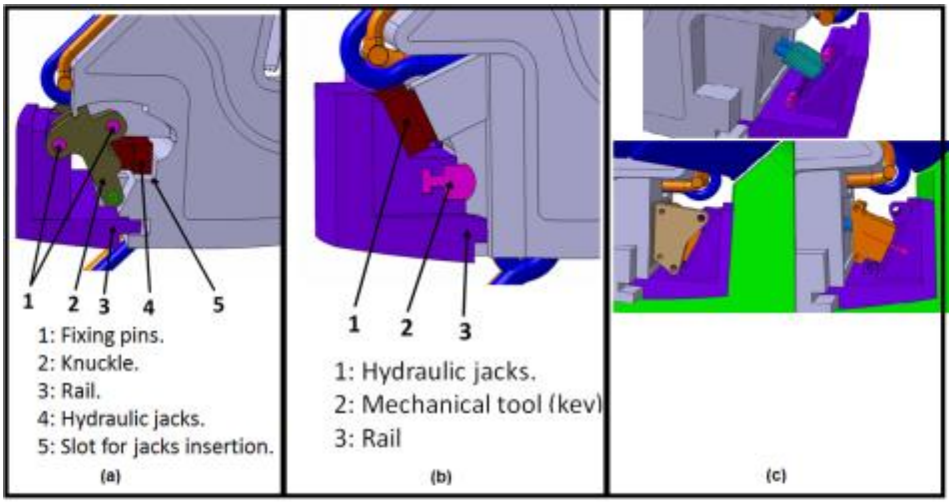


Figure 49 Third level solutions: (a) Knuckle system, (b) solution of I iteration with preloading system to avoid sliding, (c) flexible element at the outboard

On each of the develop solutions VR and Structural analyses have been developed. Here one of main benefits from the application of IPADeP was evident:

having defined from the beginning the environment for the parameters optimization and the application of refined loads, it was possible to perform more detailed FEM analyses for the solution selected during the previous iterations as well as for the new solutions proposed. Basing on the CAD model selected during previous iterations, the team working on interfacing physics was able to perform analyses to generate interface loads that fixation system should withstand.

In particular Monte-Carlo neutronic calculation (MCNP) were developed by ENEA team, as well as Electro-Magnetic (EM) calculation, while CFD calculation were developed by University of Palermo. The results of this analyses were imported in the structural analyses model prepared, allowing for multi-physics parametric analyses of the various options.

The triangulation method has been used to map the loads (body force density for EM analyses, temperature from CFD analyses and power distribution from neutronic analyses) from the different mesh types used for the different analyses and the mesh nodes for the structural analysis.

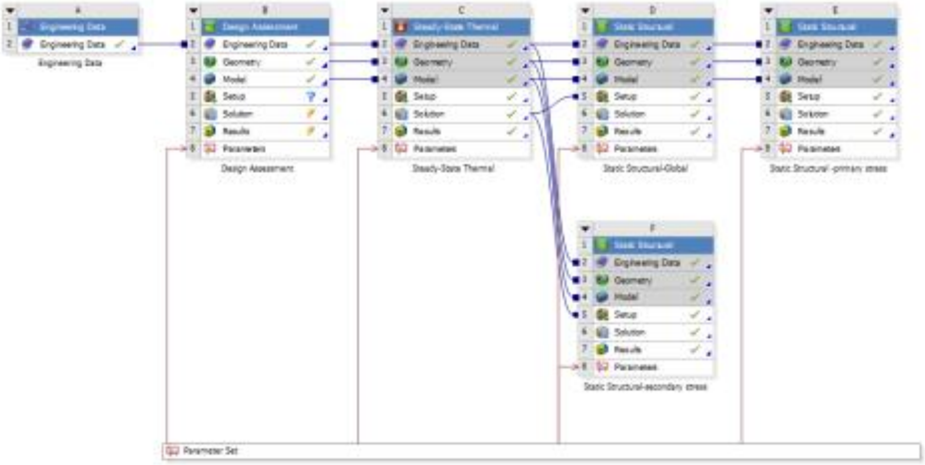


Figure 50. ANSYS workbench

Figure 50 shows the linked ANSYS workbench environment, while Figure 51,Figure 52, Figure 53 and Figure 54 show respectively the imported neutronic load, the nuclear power density, the temperature distribution and the EM loads.

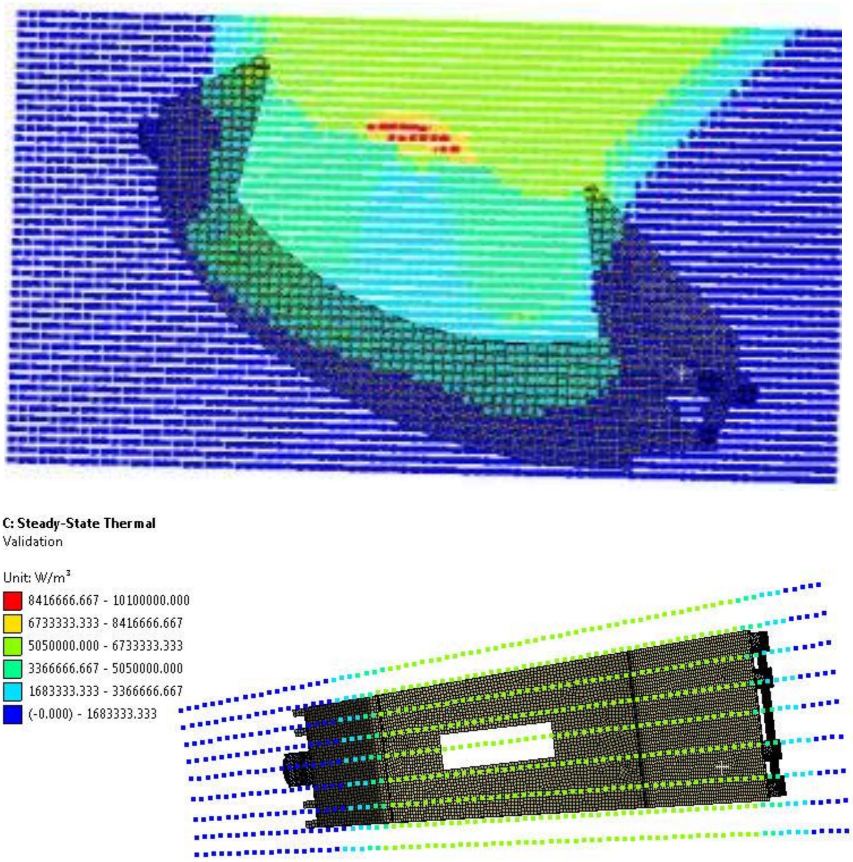


Figure 51. loads from MCNP calculation

Figure 52. Power density from MCNP calculation

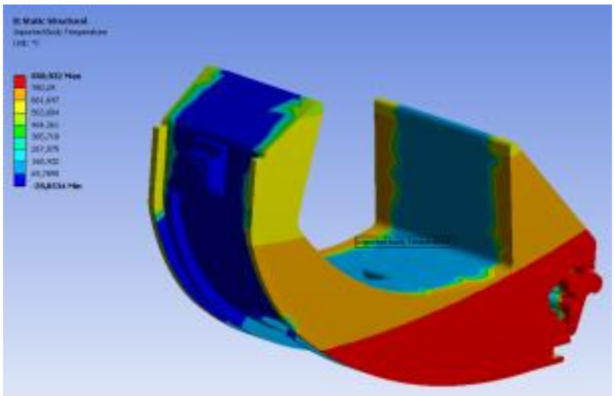


Figure 53. **Distributed temperature from Thermo- Hydraulic calculation**

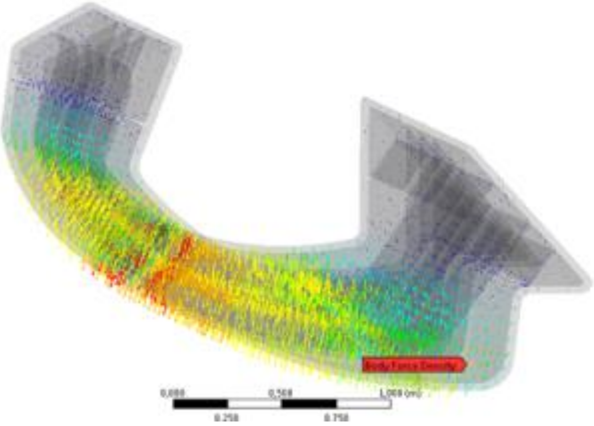


Figure 54. **Loads from EM calculation**

Assuming these detailed loads as input, the alternative solutions proposed during third iteration have been analysed in order to verify the structural requirements and each parameter (pin dimensions, contact surface magnitude, pin position) have been optimized.

The results of the structural analyses have been showed to the decision-makers with the AHP questionnaires, in order to provide an objective view against the structural requirements. However considering the high level of the design several aspects had no objective data, and the evaluation need to have the view of expert judges through the multi-criteria decision making technique. The results of AHP identified the preferred solution the “Knuckle system” (Figure 49) emerging as an improvement of the second level solution considering the new geometric constraints.

Basing on this solution the different analyses are ongoing and a System Requirements document is in preparation.

4.6 Divertor Cassette development.

During the design activities related to the fixation system, a number of requirements for the whole cassette body arose, and were analysed as important for the development of the whole divertor system and for the interfaces issues with the fixation system.

The divertor is the key in-vessel component, as it is responsible for power exhaust and impurity removal via guided plasma exhaust. Due to the intense bombardment of energetic plasma particles, the plasma-facing targets of the divertor are exposed to extreme heat flux loads. In addition, neutron irradiation produces defects and damage in the materials leading e.g. to embrittlement. Pulsed operation cause fatigue due to cyclic thermal stress variation. The complex and harsh loading environment a divertor is subjected to poses particularly challenging engineering issues that have to be solved for materializing a DEMO reactor. To this end, an integrated R&D program has been launched in the framework of the EUROfusion Consortium in order to deliver holistic solutions of a conceptual design together with the core elements of required technologies for the entire divertor system of a DEMO reactor. The essential mission is to develop and verify advanced divertor design concepts and technologies being capable of meeting the divertor system requirements defined in the European DEMO reactor development (the so-called DEMO 1).

DEMO divertor cassette pre-conceptual design has been developed starting from few high-level design requirements:

- Interfaces with blanket and vessel
- Inlet cooling water at 3.5 MPa
- Integration of PFCs cooling system
- Need to preload cassette to ensure electrical connection
- Eurofer technological limit: 40mm maximum thick plates

Since, as discussed below, for cassette body and PFCs two different operating temperature are required, two different cooling circuits are required and the integration on the cassette body represented a critical issue.

4.6.1 PFCs cooling integration on cassette body

The PFCs cooling circuit is external to the cassette body. The pipes exposure to neutron damage is one of the main issues in the design process, as well as the interfaces between feeding pipes and fixation systems. Mainly three PFC cooling options have been developed differing essentially in the position of the pipes and manifolds on the cassette upper plate.

4.6.1.1 Cooling layout option 1

Option 1 (Figure 55) is characterized by two choices: the presence of PFCs cooling feeding pipes that pass through the vacuum pumping duct in the cassette body and the presence of two manifolds on the bottom side for both inner and outer vertical target, for a total of four manifolds. Each manifolds distributes the coolant uniformly to the parallel cooling pipes of the target plate.

Figure 55. First cooling configuration option. The colour of the pipes depends on their role: the blue for inlet pipes, red for the outlet ones.

In this configuration manifolds are coupled together and are inserted into an appropriate C-shaped slot in order to protect them from the heavy radiation level inside the Vacuum Vessel.

Advantages

- Minimize interferences with supporting system, blanket and RH devices due to the position of cooling pipes and manifolds.

Disadvantages

- Pipes and manifolds are exposed and need to be shielded (the presence of a Dome is not clearly defined at time).

4.6.1.2 Cooling layout option 2

The second configuration option (Figure 56) differs to the option 1 in the fact that the inlet and outlet manifolds are not "coupled". Instead, they are located on the top and on the bottom of the vertical target, respectively.

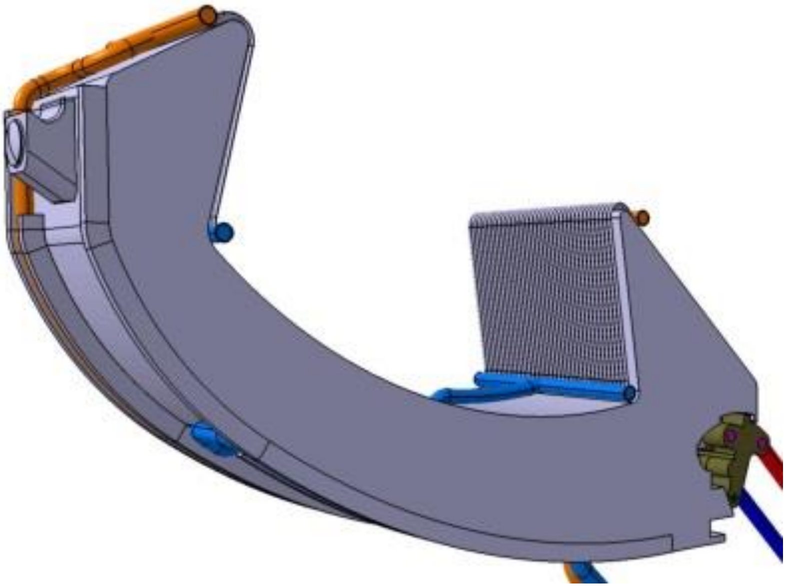


Figure 56. Second configuration option.

In this configuration the vacuum pumping duct in the cassette is crossed by two inlet pipes (instead of four) located in the centre of the duct. The inboard outlet feeding pipe runs along the whole cassette body to connect to the inboard outlet manifolds located in the region between Divertor and the Blanket.

Advantages

- Improved cooling of target PFC units (no U-turns in target cooling pipes).
- The cooling temperature at the strike point is lower than in the other two options improving the resistance against Critical Heat flux.

Disadvantages

- Both inboard/outboard inlet manifolds need to be shielded.

4.6.1.3 Cooling layout option 3

In the third configuration option (Figure 57) inlet and outlet manifolds are coupled and placed above vertical targets, in the region between the cassette and the blanket. Each outlet manifold is split into two smaller manifolds, so that inlet pipe can pass between them, and they are fed by two pipes passing below the cassette. Those pipes are joined by a manifold located in the lowest outboard region. The pipe connected to the inner inlet manifold also passes below the cassette, and joins other inlet pipes in the bottom outboard region of the cassette.

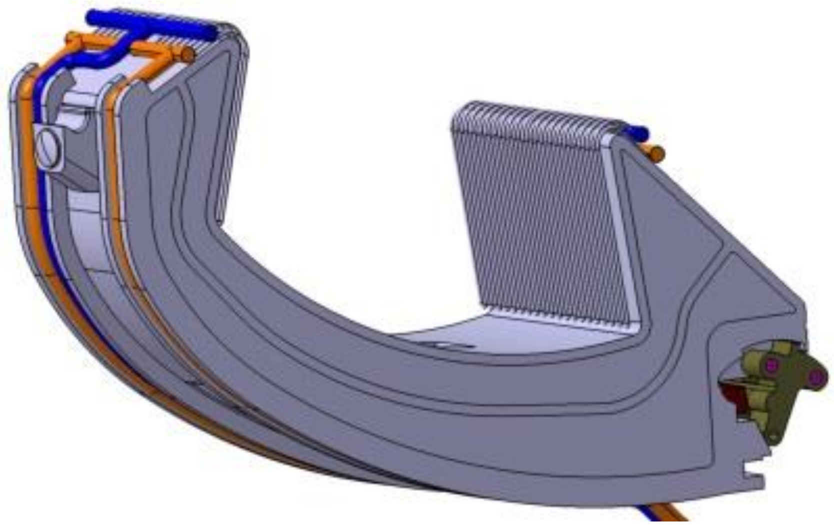


Figure 57. Third configuration option.

Advantages

- Manifolds are well shielded by the blanket.

Disadvantages

- Interfaces with blanket, supporting system and RH tools.

According to IPADeP methodology, the three options have been pair-wise compared by a team of experts using the Analytic Hierarchy Process (AHP) technique. The results showed that cooling layout option 2 is the most promising (Table 39), especially thanks to its expected best performances against the Critical Heat Flux.

Table 39 AHP results for cooling layout options

Evaluation Criteria	Options	Score
Pipes protection	Option 1	0.25
Remote handling compatibility		
Maintenance time	Option 2	0.47
Heat flux performances		
Manufacturing feasibility	Option 3	0.33

4.6.2 DEMO divertor cassette body conceptual design

The cassette surface model (Figure 58a) has been developed in CATIA V5 surface environment using a parametric approach, in order to allow easy change of ribs position and thickness during analyses optimization process. From this, the solid model (Figure 58b) has been derived, directly linked to the surface one.

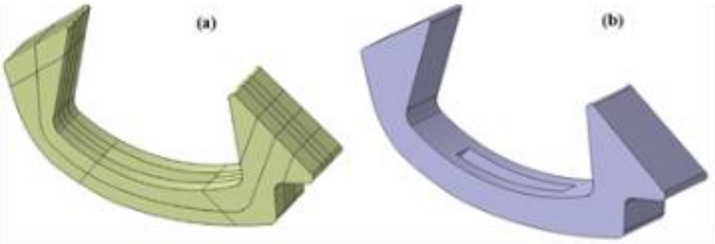


Figure 58 (a) Cassette surface model, (b) solid model.

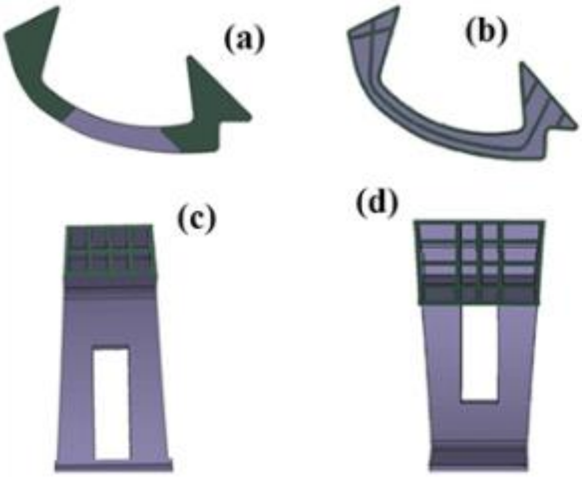


Figure 59. Cassette body layout

The cassette body is composed of an upper plate, a lower plate, side plates and internal toroidal and poloidal ribs (Figure 59). The coolant enters and exits the cassette on the outboard through two inlet/outlet pipes passing through lower port. Figure 60 shows the coolant path along radial direction.

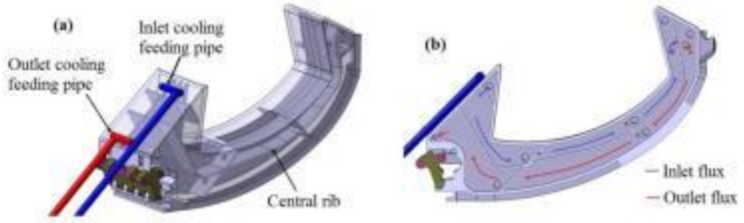


Figure 60. (a) Internal cassette structure, (b) path followed by the coolant, the central poloidal rib separates the inlet and outlet fluxes inside the cassette.

Table 40. Cassette cooling parameters.

Divertor Cassette Body	**Inlet**	**Outlet**
Pressure [MPa]	3.5	3.43
Temperature [°C]	180	210

Mass flow rate [Kg/s]	718

Dimensions chosen for the external shell and internal ribs are shown in Figure 61 and are based on the fixed cooling parameters (Table 40) (You *et al.* 2016) . Ribs are fitted with holes to allow the coolant flow through the cassette. The diameter of the holes is 70 mm almost everywhere except in the small section at the outboard where the diameter is 40 mm. Such dimensions and feeding pipes positions are optimized according thermo-hydraulic analyses, cooling parameters and preloading needs.

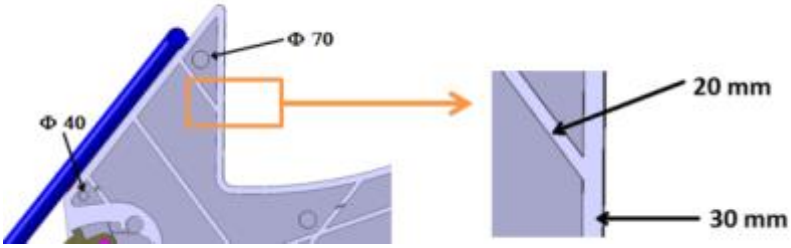


Figure 61. Ribs and thickness

In interaction with Work Package Remote Maintenance (WPRM) external ribs have been added on the lower plate to protect PFC cooling pipes in the case of a lifting platform cassette transportation concept.

The main issued driving is the design of cassette body is related to the selection of the cassette structural material and the related operation condition, discussed in the next section.

4.7 Choice of a low operating temperature for the DEMO EUROFER97 divertor cassette

In the pre-conceptual design activities for the European DEMO divertor, many materials have been proposed as for Plasma Facing components as for the divertor cassette basing on one of the fundamental design parameters such as the operation temperature range of the divertor cassette (Mazzone *et al.* 2017).

In general for material selection the starting point was been trying to use the same ITER material if possible. For the divertor cassette the austenitic stainless steel AISI 316 L(N) IG has been used as structural material in ITER. When the nuclear damage increases, as in ITER TBM (Test Blanket Module) or in DEMO in-vessel components, it is not possible to use AISI 316, because of high content of Nickel, it is subject to strong activation.

9Cr steel Eurofer is currently considered as the structural material for the cassette body as is the case for the breeding blanket. This use of Eurofer steel has significant advantages owing to beneficial properties such as reduced long-term activation and strong resistance against creep and swelling under intense neutron irradiation. The optimal operation temperature (thus the cooling condition) for the cassette is identified considering different and often conflicting requirements such as the type and allowed pressure of coolant, possible consequences of LOCA events (loss of coolant accident), limitation by design code rules and power conversion efficiency. In this paper, a material-based rationale to identify the allowable operation temperature range is discussed focusing on fracture mechanical properties.

As discussed, reduced activation Eurofer97 and RAFM steels are the primary choice materials for first wall and breeding blanket for future fusion power plants. This mainly because metals and alloys with "Body-centred cubic (Bcc)" crystal lattice structure, including iron and ferritic steels, show better resistance to prolonged irradiation than metals with "Face-centred-cubic (Fcc)" lattices. Furthermore, relevant advantages in terms of swelling behavior have been demonstrated under fission irradiation for ferritic steel (Figure 62).

Lot's information on Eurofer97 can be found in (Aiello *et al.* 2011) and (Gaganidze and Aktaa 2013) .

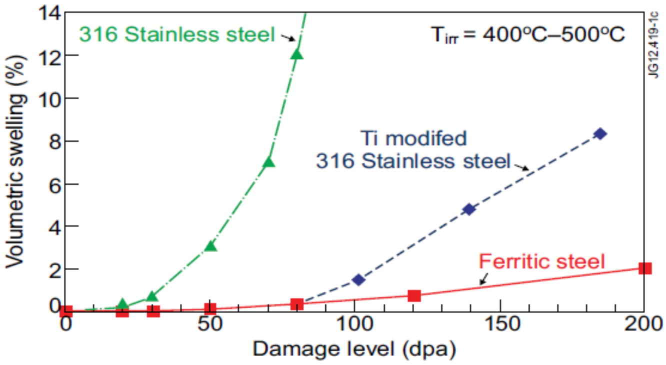


Figure 62. Swelling behaviour

As regards tensile properties, Eurofer Yeld Stress (Rp0.2) shows dependences from temperature and irradiation condition.

Figure 63 (Gaganidze and Aktaa 2013) shows Yield Stress vs test temperature for Eurofer97 in the unirradiated condition and after neutron irradiation in different medium and high dose European irradiation programmes at target irradiation temperature (Tirr) between 250 and 350 °C.

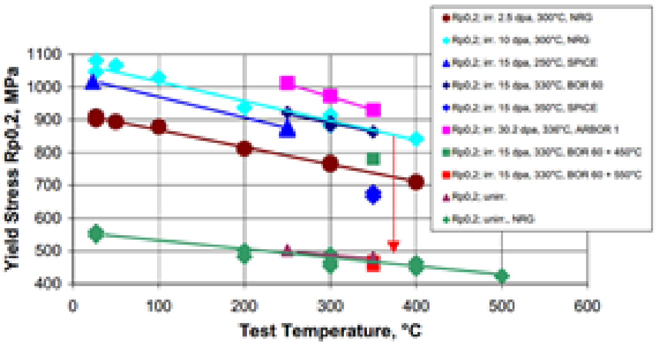


Figure 63. Yield Stress (Rp02) of irradiated Eurofer97 vs test temperature

Neutron irradiation leads to a substantial increase in the Yield Stress which is sensitive to irradiation dose and temperature. The evolution of the hardening with damage dose is summarized in Figure 63 form (Gaganidze and Aktaa 2013). Neutron irradiation leads to a substantial increase in the Yield Stress of RAFM steels with the damage dose. The Yield Stress increase is rather steep at doses below 10 dpa. The hardening rate appears to be significantly decreased at the achieved damage doses and a clear tendency towards saturation is identified. For the analysis of high dose irradiation behavior of EUROFER97 differentiation has to be done between different product forms as well as different heat treatment conditions. In fact there is a strong sensitivity of materials’ mechanical properties and irradiation performance to metallurgical parameters.

The hatched area marks the scattering band of high dose hardening for different RAFM steels.

It is important to note that the reasons for the data scattering belong not only the differences in the metallurgical variables, but also variations and uncertainties in the irradiation conditions.

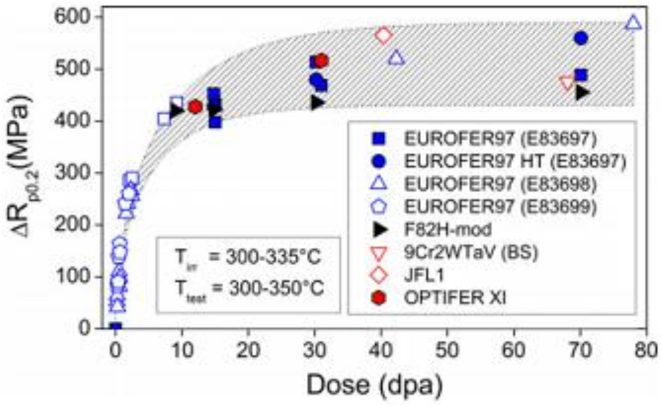


Figure 64. Eurofer Yeld Strength

Neutron irradiation of Eurofer in the temperature range below 350 °C results in strong degradation of fracture mechanical properties (in particular strong hardening and loss of ductility).

In particular with neutron irradiation on Eurofer97:

- DBTT will be raised above room temperature already after few dpa;
- Upper Shelf Energy (USE) will be reduced in comparison with the unirradiated state;
- Strong material hardening accompanied by a nearly suppression of strain hardening capability.

Eurofer fracture mechanical properties

For defining the allowable operation temperature range for DEMO divertor cassette, irradiation embrittlement has to be taken into account.

In particular the effects of temperature, irradiation and Helium production on Ductile to Brittle Transition Temperature (DBTT) and Fracture Toughness Transition Temperature (FTTT) have been investigated.

The DBTT is defined as the temperature at which the fracture energy passes below a predetermined value (Charpy(Gaganidze and Aktaa 2013) impact test). Figure 65 from shows the DBTT vs irradiation temperature for Eurofer97 and other RAFM steels.

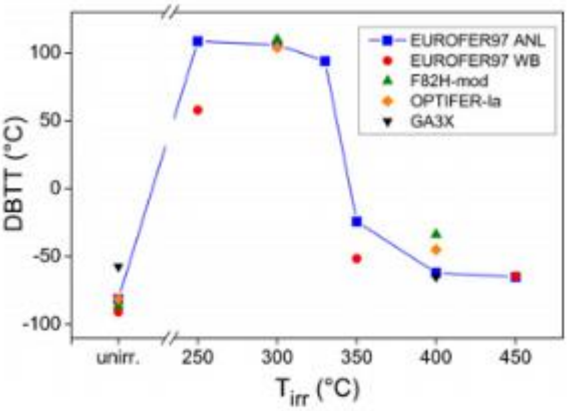


Figure 65. DBTT vs irradiation temperature for selected RAFM steels from SPICE tests (average damage dose in Spice was 16.3 dpa)

The DBTT is influenced most at low irradiation temperature (T irr <330). The evolution of the neutron irradiation induced embrittlement with dose at different irradiation temperatures is shown in Figure 66. All RAFM steels show increase in the Δ DBTT with dose below 15 dpa.

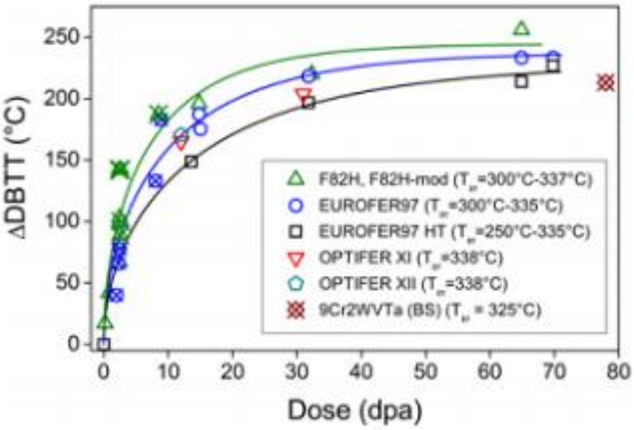


Figure 66. Shift in DBTT (Gaganidze and Aktaa 2013)

In case of EUROFER97, differentiation is made between specimens machined from as-delivered products and specimens machined from the plates subjected to pre-irradiation heat treatment (HT). The results on F82H and F82H-mod are plotted together for different heat treatments and material compositions. The pre-irradiation heat treatment (HT) of Eurofer97 leads to considerable improvement of the irradiation resistance at doses up to 30 dpa. At the achieved damage doses, however, the embrittlement of Eurofer97 HT becomes comparable to that of Eufofer97. All RAFM steels show steep increase in the ΔDBTT with dose below 15 dpa. With further increasing the damage dose the embrittlement rate decreases and a clear tendency towards saturation is observed at the achieved damage doses.

The FTT is defined as midpoint temperature between complete brittle fracture and complete ductile tearing behavior. Figure 67 shows the neutron irradiation induced shift in FTTT (Fracture Toughness Transition Temperature) and KLST (specimen according to DIN 50 115) and ISO-V DBTT for Eurofer97 vs irradiation dose. Irradiation induced shifts in FTTT are significantly larger than shifts in Charpy DBTT which indicates a non-conservative estimations on the embrittlement by Charpy test.

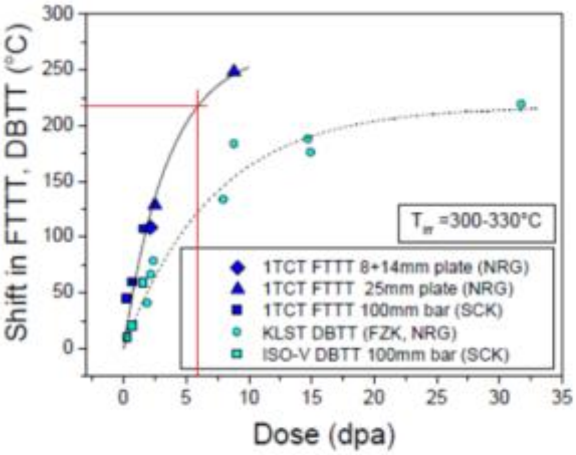


Figure 67. Shift in FTTT

There is significant uncertainty regarding the magnitude of additional embrittlement that might be introduced during fusion-relevant neutron irradiation that would generate ~ 10 appm He/dpa in steels due to helium-induced hardening.

Experiments based on neutron-irradiated B-doped RAFM steels (where additional He generation is controlled by boron transmutation) indicate the increase in DBTT from He can approach or exceed the DBTT increase associated with radiation hardening at 250-350 °C.

Figure 68 shows the additional increment of DBTT increase attributable to He production following fission neutron irradiation of B-doped Eurofer97 steels.

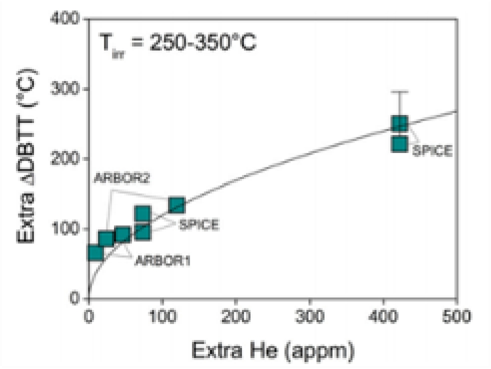


Figure 68. DBTT and FTTT for DEMO divertor cassette irradiation condition (Gaganidze and Aktaa 2013)

In DEMO it is assumed that the divertor cassette should be replaced after no more than 2 full power years (fpy). A neutronic calculationhas determined the maximum irradiation damage level in the structural material of the cassette body as 6 dpa after 2fpy. The corresponding Helium production in Eurofer was determined to be ~100appm. It can be assumed that the ductile-to-brittle (DBTT) measured in dynamical Charpy impact tests and the fracture toughness (FTTT) transition temperatures quantified in quasi-static fracture-mechanical tests are correlated but experimental results show that the two transition temperatures differ to some degree.

The DBTT of Eurofer varies with the batch number and product form. For the 1st batch of Eurofer (EUROFER97-1) the average DBTT is about -80 °C .

The FTTT of Eurofer also varies with the batch number and product form. In addition, there is an additional uncertainty in FTTT imposed by application of the standard Master Curve methodology. For the first batch of Eurofer the FTTT is about -108 °C. Application of the modified Master Curve procedure yields considerably higher transition temperature of -78°C. However, since the modified master curve methodology has not been validated yet in the irradiated state, FTTT of -108 °C in the un-irradiated condition is considered here.

Post-irradiation assessment both DBTT and FTTT concludes the following regarding the shift of the Transition Temperature after irradiation at 6 dpa:

- According to Figure 6 the DBTT of Eurofer shifts from the un-irradiated level at ~-80°C by ~123K to ~43°C;

- According to Figure 7 the FTTT of Eurofer shifts from the un-irradiated level at ~-108°C by ~225K to ~117°C.

However since Figure 67 and Figure 68 are based on material samples irradiated in fission reactors, Helium production in the material that will occur due to irradiation with high energy neutrons generated in the fusion reaction is not taken into account. DBTT shift in the range 0.5 - 0.6 K/appm He is estimated on the base of Charpy impact experiments on boron doped model steels. Hence for our case of 100 appm He an additional shift of the DBTT of 50-60K is expected. Corresponding examinations of helium effects on the FTTT shift are not known to the authors and are assumed here to be of similar magnitude. This assumption needs to be validated in future but is assumed to be conservative. Hence for an irradiation damage of 6 dpa the DBTT of Eurofer would be at ~100°C, the FTTT at ~ 180°C.

This analysis on the material behaviour generates new requirements for divertor cassette operating conditions.

Basing on these considerations, two solution for CB cooling have been proposed, the first considering water at 185 degree, the second one considering the Helium as coolant. Both will be further investigated in the following years.

5 Conclusions

The present research focused on development of a Systems Engineering process to deal with the conceptual design stage of complex systems. The main aspect characterizing the conceptual design stage were investigated, as well as the main design theories in the field, to propose an integrated design process, named Iterative and Participative Axiomatic Design Process (IPADeP). Basing on the AD theory, it provides a systematic approach to address the early stage of the design, dealing with the uncertainty of the information. Moreover proceeding iteratively layer by layer it allows an easy integration of the new requirements and subsequent design parameters, avoiding redesign cycles.

IPADeP seems to be well suited for drafting conceptual solution of large and complex systems.

The main characteristics of IPADeP can be summarized in:

1) IPADeP supports the management of new information coming late in the design process due to parallel development of high technical complex sub-systems;
2) using the proposed templates and design matrix it aims to provide good traceability of the design activities, improve design documentation and communication and reduce the needs of re-design cycles.
3) 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;
4) the design process is hierarchically structured and this allow for the integration of sub-systems and system elements.
5) The CAD-centric parametric associative model provide a useful structure for multi – physics integration and design optimization

6) The use of Fuzzy-AHP allows for a multi-criteria evaluation considering the uncertainties related to the early design stage

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. These concepts were evaluated using the Fuzzy – AHP technique, in order to take into account the "fuzzy" nature of the information at this stage. Then the design proceeded iteratively to more detailed solutions.

The application in fusion engineering demonstrated the validity of the method in dealing with the most critical issues related to the conceptual design stage. Applying IPADeP it was possible to avoid re-design cycles and to achieve a reference configuration of DEMO divertor saving a large amount of time.

Future works should focus on possible application of IPADeP in industrial case, to identify possible different needs and accordingly improve the process.

Furthermore software tools following IPADeP step and providing design activities documentation should be developed to support and to take full advantage of the implementation of the model.

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