Requirements Management in Master Model development: a case study in Fusion Engineering

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Abstract. This research focuses on the requirements management phase in the conceptual stage following a Systems Engineering approach. The development of a parametric associative master model is useful to implement requirements and available knowledge in the Computer Aided Design (CAD) model. The vertical decomposition process from higher level requirements to lower level requirements is carried out. The vertical decomposition of design parameters follows the mapping process according to Axiomatic Design principles. The functional requirements and design parameters relations enable to develop the parametric associative master model. Requirement-related modification can be automatically propagated to down-stream geometries, keeping the relationship among geometrical features in the following design steps to choose the optimal candidate. The case study deals with the mechanical design of nuclear fusion devices focusing on the improvement of the concept design of neutron shielding plates, a divertor subsystem added to satisfy a high level requirement about divertor shielding performances on vacuum vessel. Among several variants a few feasible configurations are generated and evaluated.

Keywords: Systems Engineering; Requirements Management; DEMO; Divertor; Nuclear Fusion Engineering.

1 Introduction

Concept and engineering design of large systems is a huge challenge due to its size and complexity. [1] Proper tools and methods are needed to enable the activities of geographically dispersed and specialized design teams. During the design of such systems global cooperation allows to achieve successfully projects goals.

Systems Engineering (SE) principles are consistently adopted with specific design methods allowing for a systematic approach to design since the early phase of product development [2] as an effective way to manage complexity and change. The large number of conflicting and interrelated requirements of a robust system has to be balanced. Requirement engineering is a branch of SE and is becoming widely and increasingly practiced in mechanical design. Requirements Management (RM) is not considered only the initial phase to carry out and complete at the outset of the system development, but it is connected to the whole product lifecycle for the achievement of project goals [**Errore. L'origine riferimento non è stata trovata.**]. RM concerns the collection, analysis, and validation of requirements with all the communications and negotiations inherent in working with people [**Errore. L'origine riferimento non è stata trovata.**]. An unanimous agreement concerns the relationship between the satisfaction of stakeholders requirements and the success of a project. A formal RM is justified for a complex system, or for a system that may take many years to realize [5]. Concept design starts from high level requirements and continues with a high level description of a solution.

The Axiomatic Design methodology [**Errore. L'origine riferimento non è stata trovata.**] is recognized to provide designers with a tool to structure their thought processes in the early design stage and for optimization in the design process. The design purpose is always stated in functional domain, whereas the physical solution is generated in the physical domain. AD is a logical method to create a connection between functional domain and physical domain, so called *mapping process*. The design procedure involves interlinking these two independent domains at every hierarchical level of design process providing design parameters specification from the higher qualitative level to the lower quantitative level. The design matrix and decomposition process facilitate the design documentation, the information traceability, the identification of changes impact and the achievement of design objectives.

Recent researches have shown that the top cause of troubled projects is related to the requirements that sometimes are unclear, ambiguous, imprecise and contradictory in the early design stage. When a requirement changes, it might be clearly linked to the corresponding designed feature ensuring that the final product contributes effectively to the customer objectives. After having identified initial requirements and then product functions and architectures, it is necessary to identify 3D shape and dimensions in order to verify interfacing requirements with subsystems and to carry out preliminary analyses. Master model definition focuses on a design methodology that uses the available functionalities of modern Computer Aided Design (CAD) and Computer Aided Engineering (CAE) tools to simplify variants generation during the concept design and to keep associativity between CAD and CAE environments [7, 8]. Iterative and Participative Axiomatic Design Process (IPADeP) proposed a CAD-centric design approach and a systematic thinking to support design activities in the early conceptual design stage improved with a proper Parametric Associative model [9, **Errore. L'origine riferimento non è stata trovata.**]. A PA model is a computer-based description of a geometrical model that depends on non-geometrical entities, called *design parameters*. IPADeP is an iterative process for the project optimization avoiding traditional DAER (Design-Analysis-Evaluation-Redesign) model [11].

This research work focuses on recent improvement implemented in master model development focusing on the requirements management. The case study deals with the mechanical design of nuclear fusion device discussing the improvement of the concept design of a divertor subsystem added to satisfy a high level requirement.

2 Master Model procedure

The development of a master model concept using a top-down logic for the de-sign of large and complex product should follow the workflow shown in Fig. 1.

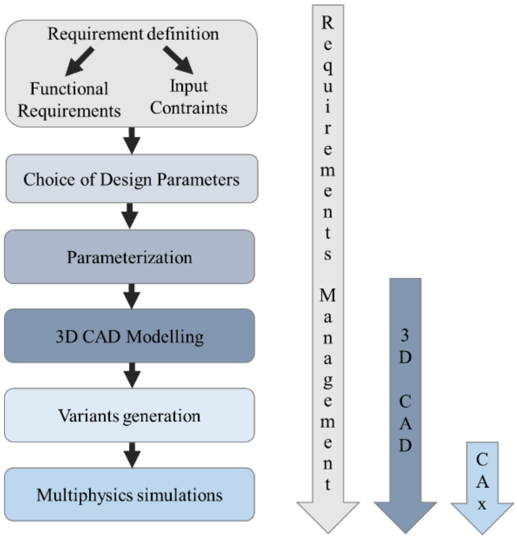


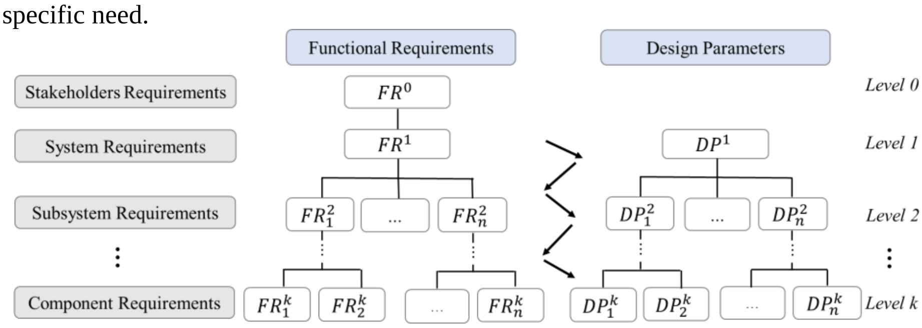
Fig. 1 - New Master Model concept definition workflow and tools.

The master model workflow is made of several phases:

- Requirements definition;
- Choice of design parameters;
- Parameterization;
- Development of a parametric 3D model for each solution;
- Generation of geometrical variants;
- Multiphysics simulations.

2.1 Requirements and design parameters identification

Functional requirements and input constraints are provided by different design team involved in subsystem design and its interfacing systems. Requirements are derived from high level requirements (stakeholder requirements) to lower level requirements (system, subsystem and component requirements). The links between different requirements in the development process is maintained by tracing requirements between different layers. During the concept design new requirements can be noticed and previous requirements can be modified. Requirements management and concept development process are strictly interrelated in the early stage of the design development. According to Axiomatic Design, functional requirements are formally defined to be the minimum set of independent requirements that completely characterizes the design objective for a specific need.



— **Fig. 2** – Vertical decomposition and mapping process.

The vertical decomposition including horizontal domains, vertical hierarchies, zigzagging, mapping emphases functional thinking (Fig.2). The design process is represented as a mapping operation, moving from a high level to a low level of FRs and DPs. The nature of mapping between a given FR vector and a DP vector having design matrix [A] is given by the design equation $\{FRs\} = [A]\,\{DPs\}$ (1):

$$\{FRs\} = [A]\,\{DPs\} \tag{1}$$

The definition of DPs matrix and their mapping in FRs helps the identification, clearly showing the design parameters of the system and which requirements can be optimized in developing a proper DP. The development of a complete solution to a given problem is proceeded by mapping FRs from a functional domain to DPs in a solution domain. The design parameters of alternative concepts are defined and documented in order to create a physical solution that satisfies requirements. The iterative nature of the design process highlights the point that a great deal of the design activity becomes redefining and redesigning of conceived ideas.

2.2 Parametric digital model development

A model specified in terms of DPs is developed; a proper small set of parameters driving the 3D geometry (namely, dimensions or properties that are most likely to be changed during the design process) has been identified in a conceptual design stage. Then a relationship between design parameters and CAD model parameters has been underlined in order to show how are related to the DPs defined by Suh. A parametric high level CAD solution has been developed. Parameter modifications are automatically propagated to down-stream applications and geometries. In the concept design the parameterization is very useful to create a relationship between different dimensions. When a value of a parameter is modified, changes are automatically propagated to the other dimensions that have a connection with the once previously modified. In this way, relationship are kept among geometrical objects and features in design process steps. Errors caused by the exchange of information would be reduced and the time consuming would be considerably less. The digital model is easy to maintain and to be changed due to the complexity of large projects that requires to use computer-aided applications for both modelling and structural assessments.

2.3 Geometrical variants generation and verification

The generation, the comparison and the evaluation among different plausible solutions has an essential role to satisfy functional requirements with minimum information with the aim to search for an acceptable solution. A parametric associative master model has to be well structured keeping a strong connection, so-called *associativity*, with Finite Element Method (FEM) analysis environment. The verification analyses represent a crucial step for communication among design teams and for understanding concepts problems, feasibility issues, individuation of possible interfaces. These potential consequences are strictly connected because the associativity between CAD-CAE environment makes the simulations quicker, easier and smarter than in the past. When the CAD model changes, the same loads and boundary conditions can be applied to different variants, without rebuilding the entire FEM simulation model. An idealization process, involving details suppression and geometrical adaptations, is often necessary. Two different models are maintained for the same product wasting of time and efforts. Modern CAE systems, like CATIA V5, provide integrated FEM tools inside the same CAD modeling platform are not suitable for complex designs that involve different physical aspects.

3 Case study: design progress of a DEMO divertor subsystem

The case study deals with the mechanical design of nuclear fusion devices. DEMO, the ITER’s successor, is the tokamak that represents the key step to demonstrate the feasibility of energy production from nuclear fusion reaction supplying electricity to the grid (Fig. 3). The work focuses on the improvement of the conceptual design of a divertor subsystem following the new master model definition workflow. It is included within the framework of the conceptual design activities of the DEMO divertor, following the results of the pre-conceptual design stage concluded in 2020 [12, 13, **Errore. L'origine riferimento non è stata trovata.**]. The neutron shielding plates shown in Fig. 4 have been added to satisfy a high level requirement about divertor shielding performances to the vacuum vessel. The design of neutron shielding plates has been carried out moving from two issues: (i) the subsystem is a container under internal pressure and, according to nuclear rules, it should pass leak test under each type of loads and load combinations. (ii) The subsystem must be integrated into the cassette body with a full penetration and continuous welding.

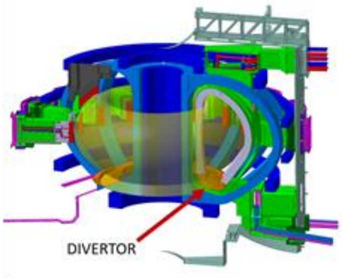


Fig. 3 - DEMO 3D CAD model.

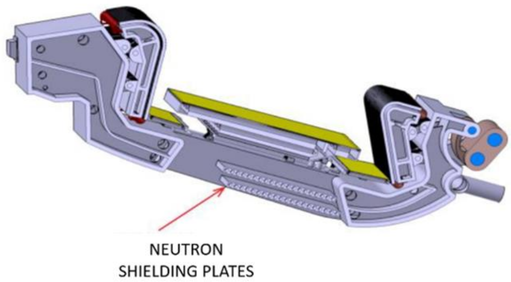


Fig. 4 - DEMO Divertor 2020 (single water cooling circuit) with neutron shielding plates.

Following the prescriptions, [15] the welded joints at boundary from water to primary vacuum shall be performed from the primary vacuum side. The previous design of neutron shielding plates has been modified to fulfil this type of welding because twenty holes need its inlet or outlet pipe. It is impossible to weld the pipes to the cassette due to the little distance between two pipes, the welding bead cannot be continuous because the welding edge is not accessible. The first step is to define high level initial Functional Requirements (FRis) and Input Constraints (ICs) as shown in Table 1.

Table 1 - Neutron Shield (NS) - Initial Functional Requirements and Input Constrains

FRi ID	**FRi Description**
FRi 1	Limit irradiation damage to the Vacuum Vessel stainless steel below acceptable levels
FRi 2	Allow for vacuum pumping performance
FRi 3	Show the properties of a robust system - withstand thermal and mechanical loads during normal and off-normal events
IC ID	**IC Description**
IC 1.1	NS shall be compatible with vacuum hole and cassette radial dimension
IC 1.2	NS shall have the same operational life of DEMO divertor

Then vertical decomposition of high level Functional Requirements (FRs) is applied according to Axiomatic Design.

Table 2 - First level of vertical decomposition and mapping

Neutron shielding plates			
ID	**FR**	**DP**	**DP type**

1	The divertor system must reduce the neutron flux if the irradiation damage at the Vacuum Vessel behind the divertor is greater than 2.75 dpa during the whole DEMO operational life.	Nuclear shielding performance	I
1.1	The subsystem shall be easy to assembly	Simple shape	II
1.2	The subsystem shall be cooled down	Serial coolant circuit	III
1.3	The subsystem shall assure structural integrity	Minimum thickness	III
1.4	The subsystem shall allow for vacuum pumping	(a)Vacuum pumping performance (b)Overall dimensions	III

The mapping process is shown in the Table 2 where first level Design Parameters DPs are identified. The design matrix (Equation 2) is useful to verify the goodness of the solution and the independence among FRs and DPs.

$$\begin{Bmatrix} FR1.1 \\ FR1.2 \\ FR1.3 \\ FR1.4 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP1.1 \\ DP1.2 \\ DP1.3 \\ DP1.4 \end{Bmatrix} \tag{2}$$

The second level of vertical decomposition of FR 1.1 and FR 1.2 is shown in the Table 3.

Table 3 - Second level of vertical decomposition and mapping

Neutron shielding plates			
ID	**FR**	**DP**	**DPtype**
1.1	The subsystem shall be easy to assembly	Simple shape	II
1.1.1	The plates shall be in minimum number to reduce material	(a) Overall sizes (b) Position inside the Cassette Body	III
1.1.2	The plates shall shield the Vacuum Vessel from neutron damage for at least 2.75 dpa.	Percentage of Steel (Eurofer97)	IV
1.2	The subsystem shall be cooled down	Pressure drop	III
1.2.1	The plates shall be able to exhaust thermal power	Percentage of water	IV
1.2.2	The manifolds shall convey the water through the holes	(a) Diameter of holes (b) Number of holes (c) One single inlet and one single outlet per neutron shield	IV

The design matrix (Equation 3) is not diagonal at this level of decomposition. So that, FRs and DPs are not independent and this is an important hint for the parameterization phase. The Axiom I is not satisfied, whereas the Axiom 2 has to be considered for the optimal concept selection.

$$\begin{Bmatrix} FR1.1.1 \\ FR1.1.2 \\ FR1.2.1 \\ FR1.2.2 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & X & X \\ 0 & X & X & X \\ 0 & 0 & X & X \end{bmatrix} \begin{Bmatrix} DP1.1.1 \\ DP1.1.2 \\ DP1.2.1 \\ DP1.2.2 \end{Bmatrix} \tag{3}$$

The third step is to generate the geometrical model of the concept that satisfy the FRs and ICs. The position and the diameter of the holes have to be defined carefully considering that they cannot be positioned symmetrically into the total area of the rectangular sector. Each plate is radially divided in two symmetrical parts, in each of them there is the same holes number. The first constrain is the dimension of two symmetrical manifolds in both halves of the plate. The manifold at the beginning of the plate has the role to collect the coolant that comes from the inlet tubes and convey it to the holes, while the manifold at the end of the plate has the mission to collect the coolant from holes and convey it to the outlet tubes. The manifolds are characterized by the same dimensions split in two symmetrical halves. The holes cannot be positioned in the middle of the transversal sector, but they can be equidistributed considering the perimeter of each manifold. According to nuclear analyses recently carried out by WPDIV team, in order to attain nuclear shielding, the percentage by volume of Eurofer and water to be respected is 70% H_2O and 30% Eurofer. The radius and the diameter has to be chosen considering it and this is one more constraint to be considered. The precise procedure has been followed. The total volume of two channels that are considered as two cylinders divided into the volume of the parallelepiped is around 0.70 in the optimal case. Since the third dimension is constant for both numerator and denominator, the length has been simplified and the considerations have been done in transversal sector. To generate and evaluate the product concepts, new solution is designed with the aid of a parametric CAD software of the Dassault Systemes CATIA V5 using a top-down modelling approach. Starting from a set of geometrical references of the product, the sub-system is designed with respect of the whole assembly considering the relationship between the parts, in order to achieve the maximum degree of freedom making changes in further steps of the design process. In order to choose the best configuration of the holes, the ratio in the equation 4 is calculated considering several values of the diameter.

$$\frac{n_H * \pi \frac{D^2}{4}}{b * h} = ratio \tag{4}$$

Moreover, the parameters that were set in order to collocate the initial sketch in the right position and to realize the rectangular matrix are six. Two of them are the vertical and horizontal distance between two holes or between the edge of the manifold and the hole (Equations 5 and 6):

$$\frac{h_M - n_r * D}{n_r + 1} = s_V \tag{5}$$

$$\frac{b_M - n_c * D}{n_c + 1} = s_H \tag{6}$$

Where h_M is the height of the manifold and b_M is the base of the manifold, n_r is the number of rows, n_c is the number of columns and D is the diameter. The position of the centre of circular sketch is calculated in Equations 7 and 8, adding to the radius the horizontal or vertical space. The centre to centre distance between two holes in horizontal and vertical direction is valuated in Equations 9 and 10.

$$x_H = s_H + r \tag{7}$$

$$y_V = s_V + r \tag{8}$$

$$Interaxis\_c = 2 * r + s_O \tag{9}$$

$$Interaxis\_r = 2 * r + s_H \tag{10}$$

When those values and, eventually, also the percentage of H_2O/SS change, the radius, thicknesses and two interaxis simultaneously change. Using the parametric model it is possible to evaluate the diameter of each configuration and understand the feasibility without calculating manually any values. In order to compare different configurations and choose the best in terms of shielding performance, it is needed to consider some options. Firstly, the percentage of H_2O/SS in the previous configuration is evaluated in Equation 11 excluding the space of the central manifolds.

$$\frac{20*\pi r^2}{b*h} = \frac{20*\pi*18^2}{1000*50} = 0.41 \tag{11}$$

For that configuration neutronic, fluid-dynamics, thermal and mechanical analyses have been already carried out, that is the reason why it has been decided to start with the same percentage of H_2O/SS simulations and then modify this value to maximize it. Therefore, a few feasible configurations are the candidates for the next comparison. In the second comparison the percentage of H_2O/SS is considered 0.5. Hence, only three configurations are selected among all the initial candidates. The holes number, the value of the diameter, the percentage of H_2O/SS are considered for each configuration in Table 5. Moreover, the vertical distance between two holes, that is the same between the manifold hedge and the closest hole, and the horizontal distance between two holes, that is the same between the manifold edge and the closest hole, are compared. Finally, the first and the third configuration have been selected and the 3D CAD model (Fig. 5 and Fig. 6) has been developed ready for further Multiphysics analyses.

Table 4 - Three best configurations.

Configuration	**Holes number**	**Diameter (mm)**	**H_2O/SS (%)**	**Vertical distance (mm)**	**Horizontal distance (mm)**
I	4	47.7	41	1.2	11.6
II	6	41.7	47	4.2	1.3
III	20	23.5	50	0.98	2.1

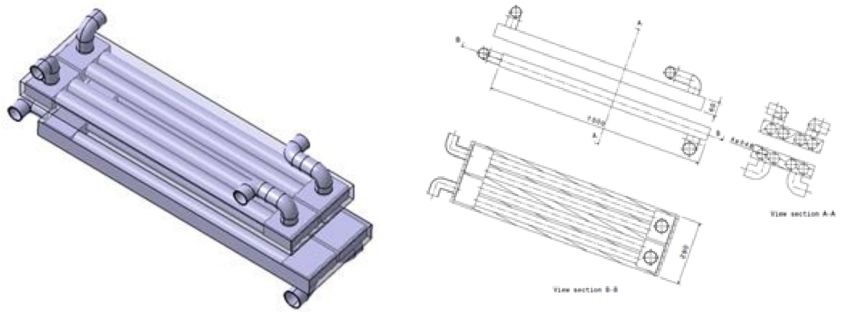


Fig. 5 - Configuration I, 4 holes. 3D model - preliminary drawing.

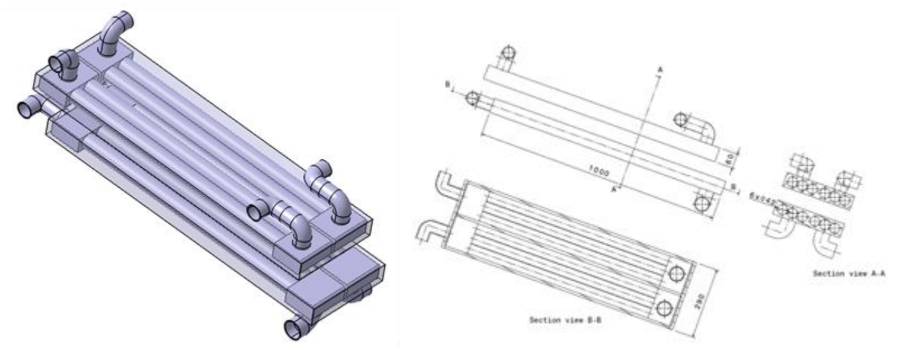


Fig. 6 - Configuration II, 20 holes. 3D model – preliminary drawing.

A parametric 3D master model has been developed adopting a CAD-centric design approach starting with design requirements and constraints and following step by step the master model concept definition workflow. Among several variants two feasible configurations were evaluated and compared. The solutions have been designed with the aid of CAD software CATIA V5. This work has been carried out at DII, Department of Industrial Engineering of University of Naples Federico II, member of the CREATE consortium, in close collaboration with ENEA Research Centre of Frascati, within the EUROfusion Horizon Europe research Framework Programmes - FP9 (2021–2027).

4 Conclusions and future works

The work discusses improvements in the development of a master model definition workflow as a systematic process in the concept design. The described workflow seems to be suitable for the design of complex and large systems. The requirements definition includes the vertical decomposition and the mapping process between functional requirements and design parameters, according to Axiomatic Design principles. Design parameters, defined by Suh, help to define parameters for the digital model. A well parameterized model allows to optimize design parameters defined at every hierarchical level. The master model helps to find a correlation between a design method and an efficient CAD model. It has been adopted in the conceptual design activities of DEMO divertor subsystem from few high-level requirements to some high level conceptual solutions. Main high level requirements of the neutron shielding plates have been investigated underlying their importance in the cassette body. Starting with the requirements management of this subsystem the vertical decomposition of functional requirements and the identification of the design parameters have shown how the lower level requirements are interrelated each others. This means that from a lower design parameter it is possible to go back to more than one functional requirement. This is a key step to the development of a master model concept of the neutron shielding plates because a single design parameter can be connected to many functional requirements. Moving from the most recent model of the plates, design issues have been investigated with the aim to improve the solution. A 3D CAD model with a set of parameters has been developed. Among a large number of possible variants, only two configurations have been selected and compared. Both feasible variants are potentially able to satisfy nuclear and vacuum pumping performances and to solve new highlighted design issues. The geometrical model will allow to carry out sequential Multiphysics analyses such as fluid dynamics, neutronic, electromagnetic transient, thermal and structural analyses. The results will be important for verification and validation phases. Further works could concern the development of a parametric associative model that will be useful to shorten the time to complete simulations and to share results in real time.

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