WPBB-CPR(18) 20291

G.A. Spagnuolo et al.

Systems Engineering approach in support to the breeding blanket design

Preprint of Paper to be submitted for publication in Proceeding of
30th Symposium on Fusion Technology (SOFT)

Systems Engineering approach in support to the breeding blanket design

Gandolfo Alessandro Spagnuolo[a], Gaetano Bongiovì[a], Fabrizio Franza[a], Ivan Alessio Maione[a]

[a] *Karlsruhe Institute of Technology (KIT),Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany*

Nowadays the Systems Engineering (SE) methodology is strongly applied in several fields of engineering and it represents a powerful interdisciplinary mean to enable the realisation of complex systems taking into account the customer and Stakeholder´s needs. Also in the fusion community, this theme is becoming increasingly pressing and the implementation of the SE approach, from the early stage of design, is now a must. Indeed, within the framework of EUROfusion activities, the SE method has been selected for capturing the system and interface requirements and for their management and verification with particular focus to the Breeding Blanket (BB) System of the European Demonstration Fusion Power Reactor (DEMO). Specifically, various levels of functions and requirements have been elicited and a sophistication of the BB SE model, set-up using the Systems Modelling Language (SySML), has been performed. This paper describes the advantages of applying a SE approach to the BB design considering, in particular, the BB requirement development and management and the definition of the interfaces between the BB and the major interconnected systems, including Remote Maintenance, Balance of Plant, Vacuum Vessel attachment, Heating and Current Drive and Fuelling Lines Systems. An effective application of the SE technique to the pre-conceptual design phase of the BB is also provided in this paper.

Keywords: Systems Engineering, breeding blanket, requirements, interface, functional architecture.

1. Introduction

The design of a fusion power plant, like the European Demonstration Fusion Power Reactor (DEMO), represents nowadays one of the most challenging efforts for the scientific and technological community. Indeed the complexity of DEMO is due not only to the uncertainties related to the physics and the used material, but also to the big number of systems required for its operation (i.e. more than 40 systems have been identified at level 1 of the Plant Breakdown Structure (PBS) [1]) which leads to an huge number of interfaces among them [2] [3]. If, together with these issues, the number of alternative configurations foreseen for the reactor [3] and for some systems such as the Breeding Blanket (BB) [4] is taken into account as well, it is immediately clear the necessity to address the DEMO design in a holistic way, adopting for instance a multiphysics ([5], [6] and [7]) or a Systems Engineering (SE) approach. In particular, in this paper attention is paid to the SE approach, as already done in ITER [8], with the aim to:

- capture, trace and maintain coherency between systems requirements;
- manage large number of sub-system interdependencies;
- develop an holistic configuration to better understand the functional, spatial and physical integration aspects.

For these reasons and following the path already traced for the top level design of DEMO reactor [3], it has been decided to slope down the SE methodology to the BB system level. In particular, in this work, it is given a broad overview of the SE application for the development and management of the BB requirements (in Section 3), for the definition of the interfaces between the BB and the major interconnected systems, including Remote Maintenance (RM), Balance of Plant (BoP), Vacuum Vessel (VV) attachment, Heating and Current Drive (H&CD) and Fuelling Lines (FL) (in Section 4), and (in Section 5) for the definition of the logical/functional architecture using the Systems Modelling Language (SySML).

2. Systems Engineering overview

The SE is defined as an interdisciplinary field that, using a holistic approach, covers all the engineering disciplines focusing the attention on how to design complex systems from concept to disposal [9]. Thanks to its intrinsic multidisciplinary nature, the SE provides a powerful means for the elicitation of systems requirements, for the identification and definition of the interfaces and for the exploration of architectural agnostic solutions using a functional analysis. The SE has been already applied at DEMO plant level as described in [10] and its further development in the BB system is described in the following paragraphs.

3. BB system and requirements

During the DEMO pre-Conceptual Phase, four different BB concepts have been studying and designing [11] in Europe: Helium Cooled Pebble Bed (HCPB), Water Cooled Lithium Lead (WCLL), Helium Cooled Lithium Lead (HCLL) and Dual Coolant Lithium Lead (DCLL). The four BB options, according to their own characteristics, share functions and requirements that are captured in the System Requirement Document (SRD) [12] and managed using the IBM Rational DOORS database. The hierarchical document architecture adopted in DEMO and consequently in the Work Package BB (WPBB) is reported in Fig. 1. Following the SE approach, the stakeholder requirements are derived to plant level

---

author's email: alessandro.spagnuolo@kit.edu

requirements in the Plant Requirement Document (PRD) and satisfied by the plant architectural design presented in the Plant Definition Document (PDD). Subsequently, the plant requirements are declined to the system level, like the BB, in the SRD and realized by the system designs presented in the corresponding System Definition Document (SDD).

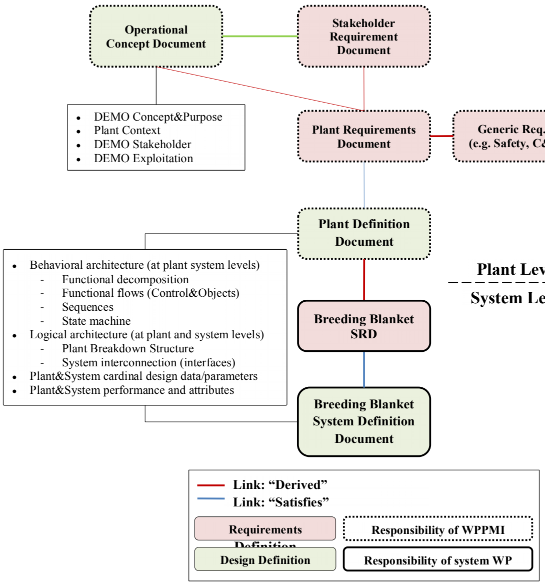

Fig. 1. Hierarchical document architecture [12].

3.1 Context diagram

Following the SE approach reported in [13], the system context diagram of the BB has been drafted (Fig. 2) in order to define the boundaries between the BB and its environment highlighting the interactions that may occur. In this way, it is possible to position the BB in a context and graphically portray the large intercommunication with other systems.

3.2 Requirements management

The SRD has been organized as a tabular data document according the specific template readable in DOORS. Specifically the following columns are used:

- ID number. It is the object identifier in DOORS.
- Object type. It reports the type of the corresponding row (Heading, Information, Figure, Table, etc.)
- Req. Cat. It is the requirement category.
- Object. Description of the requirement or of the corresponding field.
- Priority. This field is limited to the following values:
    - mandatory (for those requirements that must be met in order to produce a valid system);
    - desirable (expresses additional features of the system which, although they add value, are not essential).
- Rationale. It identifies the requirement rationale. In this field it is also specified if a requirement is referred to a specific concept. When the requirement applies to the four concepts, this information is omitted.
- Source. When applicable, a reference to EUROfusion document database is provided.
- Req. Comments. It reports general comments on the requirements.

Presently, in the DEMO pre-Conceptual Phase, more than 120 functional and performance requirements have been identified for the BB system and conveniently subdivided between the safety, design, operation, maintenance and quality fields [12]. The description of BB system and sub-systems, boundaries, interfaces and operation states has also been included.

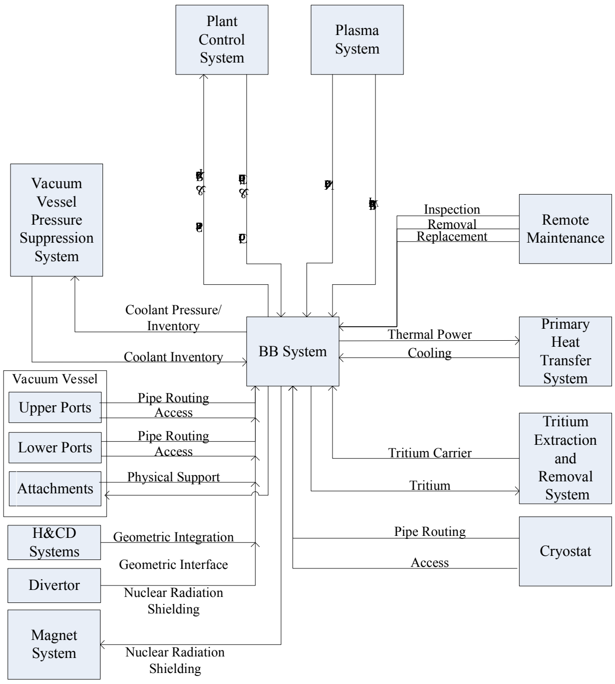

Fig. 2. BB system context diagram [12].

4. BB interfaces definition

One of the most important and challenging topic in a complex system is the identification, definition and management of the interfaces. As already highlighted in [4] and [11], the integration, inside the tokamak vessel, of complex systems is of vital importance but, at the same time, its realization is complex and, if not addressed from the early stage of the conception, it can produce unexpected delays with a consequent increase of costs.

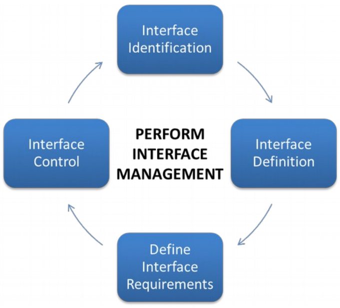

Fig. 3. Interface management process steps [14].

For these reasons, following the SE approach, it has been decided to face this issue from the beginning in the WPBB. The interface identification and numbering have

---

author's email: alessandro.spagnuolo@kit.edu

followed the rules described in the Interface Management Plan [14] based on 4 process steps as shown in Fig. 3. This methodology has been applied in particular to the main BB interfacing systems like RM, BoP, VV attachment, H&CD and FL. For each interface, using the SE approach, three documents have been produced, namely:

- **Interface Control Document (ICD).** The ICD is primarily a management view of an interface between two PBS elements containing overview information and a list of all the interfaces identified between the PBS elements.
- **Interface Definition Document (IDD).** It contains the technical information required to define the interface.
- **Interface Requirement (IR).** Each System has a corresponding module within DOORs where all interface requirements are stored.

Remote Maintenance interface

More than 100 interface requirements have been captured and defined in IR document between the RM and the BB systems. The fruitful work, conducted in collaboration with the RM team, has allowed a better alignment of the working hypotheses used by the two project teams. Indeed, particular attention has been dedicated to the definition of requirement related to the draining of operational fluid and the minimization of their inventory inside the BB segment as well as their solidification prior to RM operations.

Furthermore, efforts have been devoted to the definition of the lifting interface, determining the maximum interface temperature (i.e. 100 °C) to be kept during the RM engagement, the maximum BB segment weight (ca. 80 tons) and the dimension and routing of the BB pipes through the ports. All these aspects are going to be used as boundaries for the development of the design in a congruent way among the BB and RM design teams. It has to be noted that some BB-RM interface requirements are design-driver also for other BB interfacing systems. In fact, the design of systems such as, for instance, H&CD does not have to modify the BB features required by the RM system in order to correctly perform the foreseen RM operations.

Balance of Plant interface

Ranges of temperature, pressure and mass flow rate values during the plasma operational state have been defined and captured in the interface requirements. Although the definition of the processes is still at the early stage, a preliminary identification of the requirements for the draining&draying as well as for the decay heat removal of the BB has been drafted. This activity is summarized in the 11 interface requirements captured for the BB and BoP systems interface.

Vacuum Vessel attachment interface

About 10 interface requirements have been currently elicited between the BB and VV systems mainly aimed at the definition of gaps, loads and positional features of attachment system.

Heating and Current Drive interface

More than 30 interface requirements have been defined between the BB and H&CD system with particular attention to the Electron Cyclotron (EC) and Neutral beam Injector (NBI) subsystems. For instance, these sub-systems might have a big impact on the BB design because they may compromise the poloidal integrity of the BB as well as some performances in terms of shielding capability or tritium production. Moreover, additional thermal loads may be potentially exerted on the BB during H&CD operating phase and proper cooling system may be necessary, having potential implication also on the BoP system layout.

Fuelling Lines interface

Further 18 interface requirements have been captured between the BB and FL systems finding a compromise among the preferable pellet trajectory insertion and the arrangement of the FL behind the BB segment.

5. SysML BB case study

The work has been directed to further develop the system operational concepts and the supporting functional architecture of the BB system, already addressed within the work previously done in [10]. The hierarchical structure of such an approach, to apply to a specific engineering system (here the BB system) consists of three main constituting blocks:

- System architecture, where functional, logical and physical architectural levels, as well as the system operational concepts, have to be defined. The functional architecture pertains to a solution-unrelated description of the design, being composed of a purely functional (and generic) representation of the system. The logical architecture offers a conceptual description of the system elements, where design variants can be identified and should capture the system architecture. The physical architectural level encompasses the characterization of all the components at their physical niveau, i.e. considering the component behavioural features. A system operational concept is a structured representation of how a system works internally and interacts with its boundaries (in terms of materials, energy and information flows), informing the requirements and including all the operational scenarios associated with the lifecycle concepts.
- Definition of modelling processes, including the traceability to and from operational concepts and functional architecture to system requirements. The system requirements are refined by operational cases, while derived requirements are allocated to defined functions.
- Illustration of system boundaries and model elements. The multiple functional and system element options (if any) feature alternative interfaces to the neighbouring systems, which need to be accounted

---

author's email: alessandro.spagnuolo@kit.edu

for. Having at disposal a spectrum of design options (for the BB system or any other DEMO plant component) allows a flexible design of the whole DEMO plant, i.e. granting a highly holistic fashion.

The activities mainly focus on the functional architecture of the BB system, where a set of functions, previously defined as per Model Based Systems Engineering approach and elaborated in SysML, are being further refined.As example the particular case of on “Contribute to Plasma Stability” function is herein considered (Fig. 4).

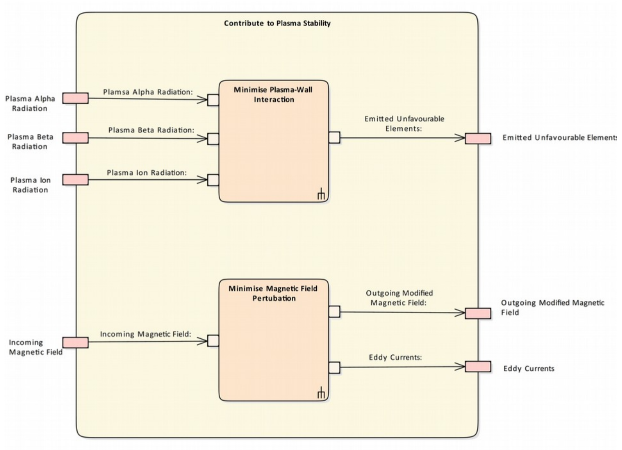

Fig. 4. New Integrated Operation during Plasma Operating State [15].

Two related goals have been identified:

- contribute to plasma stability minimizing the magnetic field perturbation.
- contribute to plasma stability minimizing plasma contamination due to ejection of plasma facing materials.

From a functional standpoint, the particle and the magnetic field interactions between the blanket and the plasma systems represent two figures of merit to be minimized. In fact the BB system, by means of dedicated measures, shall attempt reducing such complicating aspects. For instance, an appropriate alignment of the blanket first wall with respect to the magnetic field lines in the Scrape-Off Layer (SOL) can potentially hinder the particle emission from the interfacing materials, influenced by incoming alpha, beta and charged particle radiation, to the plasma SOL. Charged particles interact with the magnetic field and can be transported to the core plasma region across the SOL. As a result, they may endure into the twofold set-back of altering the plasma dilution (hence, the conducting properties) and poisoning the thermonuclear fusion reaction via radiative dissipative loss power (e.g. line radiation). Furthermore, high impurity fractions in the edge region may endure into high radiative losses, which can considerably cool down the plasma and bring it to thermal instabilities, such as multifaceted asymmetric radiation from edge (MARFE). Accordingly, the emission of particles from the blanket to the plasma system, arising from interactive processes (such as sputtering and recycling) of the first wall with impinging alpha, beta and charged particles, shall be minimized. Moreover, due to some specific blanket design-related morphological features, undesirable perturbations of the static magnetic field spatial profile can occur. For instance, the openings in the breeding blanket associated with the integration of the auxiliary systems, introduce asymmetries in the magnetic field distribution, yielding an increased toroidal field ripple on the plasma last closed magnetic surfaces. As the field ripple is figure of merit directly interconnected to plasma stability, it has to be minimized as well.

6. Future work

As described in [3], for the end of 2020, it is foreseen the completion of the DEMO pre-Conceptual Phase with the aim to select the highest likelihood plant concept to be investigated in the next Conceptual Phase. In this framework, during the next two years, the SE activities will be continued in order to further develop the top level documents necessary for 2020 gate review. Inside the WPBB, particular emphasis will be given to the sophistication of SRD and interfaces documents as well as to the validation at level 2 of PBS and Functional Breakdown Structure. Efforts will be also dedicated to the realization of the Load Specifications Document and the Preliminary Compliance Assessment report for the verification of design compliance with the set of requirements and specifications.

7. Conclusion

Within the framework of EUROfusion activities the SE approach has been selected, from the early stage of conception, as methodology for the capture and management of system and interface requirements, for the supervision of sub-system interdependencies and for development of a holistic configuration to better understand the functional, spatial and physical integration aspects. This approach has been declined from the plant level down to the system level like the BB. Efforts have been dedicated to the definition of system requirements and their traceability has been ensured using a systematic SE method as well as by means of the IBM Rational DOORS database. Particular actions have been undertaken in order to identify the interfaces, to define the interface requirements (ca. 170 new ones captured) to keep the consistency between the system and interface requirements, respectively.

Moreover, the coherency among the interface requirements has been also taken into account transferring the restrictions and boundaries applied by one system to the BB to the other interfacing systems.

Finally, a functional architecture has been developed and further sophisticated in order to have at disposal a systematic way to replicate a complex system (such as the BB) keeping the possibility to explore multiple design options against the required functionalities.

Acknowledgments

---

author’s email: alessandro.spagnuolo@kit.edu

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] T. Franke, DEMO Plant Breakdown Structure (PBS) (2MJ6WB v2.5).

[2] C. Bachmann et al., Overview over DEMO design integration challenges and their impact on component design concepts, FED, 2018, ISSN 0920-3796, https://doi.org/10.1016/j.fusengdes.2017.12.040.

[3] G. Federici et al., DEMO design activity in Europe: Progress and updates, FED, 2018, ISSN 0920-3796, https://doi.org/10.1016/j.fusengdes.2018.04.001.

[4] F. Cismondi et al., Progress in EU Breeding Blanket design and integration, FED, 2018, ISSN 0920-3796, https://doi.org/10.1016/j.fusengdes.2018.04.009.

[5] G. A. Spagnuolo et al., Identification of blanket design points using an integrated multi-physics approach, FED, Vol. 124, 2017, pg. 582-586, ISSN 0920-3796, https://doi.org/10.1016/j.fusengdes.2017.03.057.

[6] G. A. Spagnuolo et al., Development of helium coolant DEMO first wall model for SYCOMORE system code based on HCLL concept, FED, 2018, ISSN 0920-3796, https://doi.org/10.1016/j.fusengdes.2018.03.003.

[7] F. Franza et al., Development of an advanced magnetic equilibrium model for fusion reactor system codes, FED, 2018, ISSN 0920-3796, https://doi.org/10.1016/j.fusengdes.2018.02.014.

[8] S. Chiocchio et al, System engineering and configuration management in ITER, Fusion Engineering and Design, Vol. 82, 2007, pg. 548-554, ISSN 0920-3796, https://doi.org/10.1016/j.fusengdes.2007.06.019.

[9] INCOSE UK. Z-Guides. Accessed: May 2017. http://incoseonline.org.uk/Program_Files/Publications/zGuides.aspx.

[10] D. Wolff et al., "Early Lessons From the Application of Systems Engineering at UKAEA (May 2017)," in IEEE Transactions on Plasma Science, vol. 46, no. 5, pp. 1725-1734, May 2018. DOI: 10.1109/TPS.2018.2819726.

[11] F. Cismondi et al., Progress in EU-DEMO in-vessel components integration, FED, Vol. 124, 2017, pg. 562-566, ISSN 0920-3796, https://doi.org/10.1016/j.fusengdes.2017.03.147.

[12] I. A. Maione et al., BB System Requirements Document (SRD) – Release 2017, EFDA_D_2NASBT.

[13] L. J. Bronwyn et al., INCOSE Systems Engineering Handbook – Visual Enhancement to Support Understanding, Conference Paper, May 2011.

[14] C. Jackson, PPPT Interface Management Plan, EFDA_D_2N5PKH.

[15] G.A. Spagnuolo et al., Report on system engineering activities, including SEPOC role, EFDA_D_2MY335.

---

author's email: alessandro.spagnuolo@kit.edu