Design space exploration for architecture selection: Radial Neutron Camera nuclear fusion diagnostic study case

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ABSTRACT

System engineering is an established methodology meant to support engineering design activities for complex systems design. Nuclear fusion devices design complexity derives from contextual presence of both a challenging operating domain requiring frontier technology and a restrictive regulation on safety or systems compatibility aspects. System engineering methodologies adapted to nuclear design environment reduce risks of late design changes related to compatibility problems emerging at integration stage. Present work describes the methodology developed for the conceptual design phase of a nuclear fusion neutronic diagnostic, the Radial Neutron Camera for ITER plant. In particular the focus is on the characterization of design intents and the structured exploration of design domain aiming at baseline architecture to be engineered in next design phase. A formal definition of design domain space in terms of architectural elements has been developed to allow the instantiation of a set of candidate options. The instantiation process was structured according to sub-system intrinsic information content and potential mutual impact. Finally, architectural options have been assessed according to a specifically defined ranking function able to integrate information characterizing the candidate architectures deriving from different domains enabling a close collaboration with stakeholders.

1. Introduction

Systems engineering (SE) is a body of established techniques meant to support engineering design activities [1] providing added value especially for complex project exploiting technologies with low maturity level. Aerospace applications, initial culture medium for SE approach [2,3], exemplify such type of engineering design domain. Main challenges in such domains come from the mixture of both demanding performances and operating environment requiring in turn the development of innovative systems forcedly characterized from poor experience.

Nuclear Fusion plants design shares similar design domain challenges with aerospace systems. The main goal of nuclear fusion plant is to achieve a controlled extraction of the energy release associated with the fusion reaction between hydrogen isotopes deuteron (D) and tritium (T) according to (Eq. (1))

$$D + T -> {}^{4}He\ (3.56\,MeV) + n\ (14.03\,MeV) \qquad (1)$$

The challenging operating domain requires the exploration of new and contextual solutions emerging from technological frontiers (e.g. cryogenic cooling, superconducting magnets, new materials able to withstands specific loads). The feasibility of such solutions on the other hand must be assessed taking into account general constraint on system safety, reliability and availability features in order to achieve the scientific program goal: to demonstrate an energy gain (net thermal power out / heating power in) of the order of 101. Note that the exploitation of such energy is demanded to DEMO fusion reactors currently facing pre-conceptual design phase [4]. Despite the complexity of the project witnessed from mentioned issues, only recently the SE design methodology has started permeating design process [5–8]. Nuclear Fusion context is also characterized by very long design cycle and a large set of stakeholders. Stakeholders mainly include e.g.: ITER Organization (IO), which defines system drivers, nuclear safety authority of hosting country, which enforces safety requirements and scientific institutions as well as industry supplying system design and manufacturing. System mission is derived from design drivers while design domain is constrained by several requirements emerging from the integration of the considered system into its operating environment.

This context implies a complex structure of requirements in response to different actors (e.g. vacuum responsible, safety officers, auxiliaries' suppliers, etc.). Requirements might have unclear prioritization and occasionally happen to be possibly conflicting when

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applied to actual design solutions. Requirements set might also happen to change over time (e.g. the interface requirements) or can be better specified only during the conceptual design process, since they come from the advancements achieved on interfacing systems. Hence the need of a structured methodology able to capture design intents and provide a pool of feasible system architecture instances from which to select the baseline candidate for detailed design. Moreover the long design cycle (about 10–15 years) exposes designers to the risk of increasing impact of late design changes due to unforeseen needs or upcoming constraints. Hence the necessity of a correct representation of stakeholder prior needs as well as a clear domain definition allowing for flexibility and efficient management of project change [9]. Note that design domain, i.e. the space of feasible solutions, emerges from the intersection of designer ability to develop/adapt currently available technology with project constraints (e.g. requirements, interfaces, budget, technology constraint, time to deliver, etc.).

The focus of present work is on the design process model implemented for Radial Neutron Camera (RNC), an ITER diagnostic system devoted to the measurement of the neutron emissivity (number of neutrons per second per m^3) radial profile associated with plasma. RNC diagnostic is essential for calculating some specific fusion reactions metrics, such as fusion power density, indirectly obtained by measuring the number of the neutron emitted from a given space portion over time. The RNC diagnostic exploits the tomographic imaging principle to obtain the mentioned emissivity profile [10,11]. In particular, with reference to Fig. 1, the plasma (organized into nested Toroidal flux tubes, of which a section is shown) is sampled by straight lines of sight (LOS). These lines of sight ideally represent the path of neutrons emerging from nuclear reactions in the considered portion of plasma and reaching neutron detectors after collision-free straight flights. Detectors (not shown in Fig. 1) are ideally placed somewhere on the right along the LOS. Note that, neutrons are emitted in all directions from plasma, so that to select the uncollided neutrons, specific collimators are needed to shield as much as possible detectors surfaces from background-scattered neutrons.

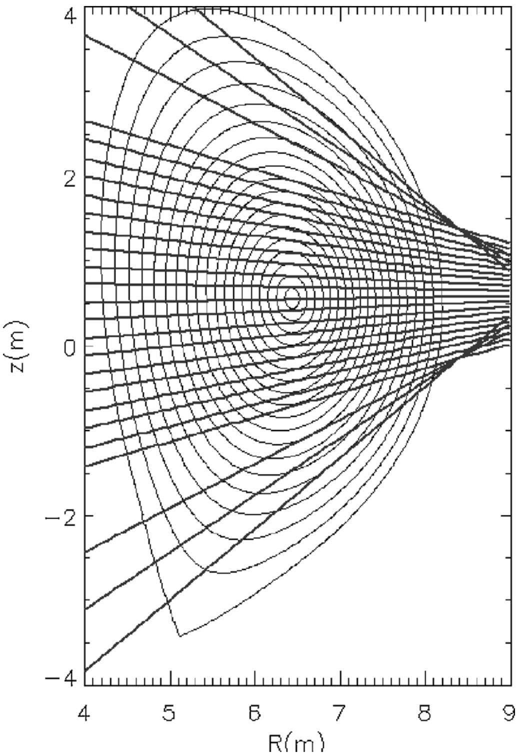

Fig. 1. Lines of sight spanning plasma for tomographic imaging.

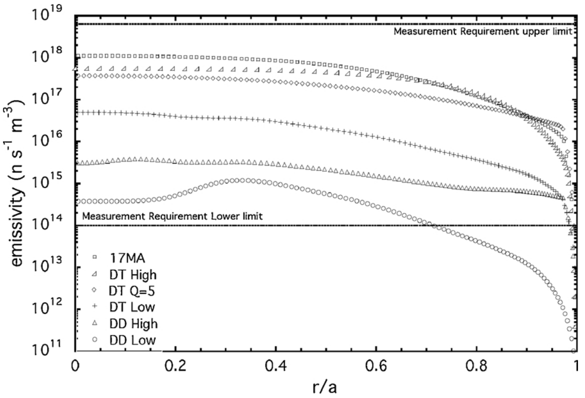

Fig. 2. Reconstructed emissivity profile for various ITER plasma scenarios.

Information about neutron counts and spectrum is provided at detector location. Fusion neutrons present energy peaks corresponding to 14.03 MeV in Eq. (1) and (2).45 MeV corresponding to deuterium-deuterium reactions (D + D - > ^{3}He (0.82 MeV) + n (2.45 MeV). Note that in Fig. 1 plasma upper and lower edge are covered by a set of sloped lines, which intercept before Vacuum Vessel port, henceforth requiring detectors to be placed "in-port" (to be differentiated from the rest of LOS ending in an ex-port detection system). Detectors at the end of a LOS register the information. The number of neutrons emitted along each LOS detected at the right end of the LOS (Fig. 1) is then processed by means of tomographic inversion algorithm also exploiting plasma geometrical symmetries at equilibrium configuration [12]. This way the neutron count measure at several locations is transformed into a single curve, shown for several ITER scenarios in Fig. 2, estimating the neutron emissivity profile (i.e. number of neutrons emitted per second at a given spatial location) over a normalized (*r/a*) spatial dimension going from plasma core (*r/a = 0*) to plasma edge (*r/a = 1*), with normalizing factor *a* being the torus minor radius.

Moving from the mentioned diagnostic concept, a design space exploration work has been carried in the framework of conceptual design of RNC system, with the goal of achieving an unbiased exploration of design space leading to the identification of candidate design architectures, among a set of feasible ones, and eventually providing the best baseline architecture in output. The implemented methodology is schematically summarized in Fig. 3. It aims to support the left side of the SE V-model [8,36], managing the requirements and driving the designers through the design identification and architecture selection. First, design drivers and the body of documents describing ITER plant, design procedures and operating domain (Design description, operating environment description (e.g. Vacuum, Electromagnetic loads, etc.)) were acquired in order to define RNC context. Then design intents were captured in terms of functions deriving from such main design drivers. Also a set of logical sub-systems emerging from defined functions was identified in this step. Then design domain was specified by means of a set of architectural elements spanning the design domain. Boundaries of such domains were contextually identified on the base of requirements or technology constraint. Then a set of candidate architectures was instantiated in the form of specific configurations of architectural elements. To support this process, sub-systems were prioritized according to their intrinsic information content and potential impact onto other sub-systems, so to have a sub-set of main sub-systems leading the architecture candidate instantiation process. A set of performance metrics was then defined to evaluate proposed architectural options according to a ranking function and obtain a first architectures ranking. Then such architectures were further detailed and improved in terms of technological implementation in order to enable a fine assessment of possible show-stopper, safety or RAMI problems. Finally the baseline best architecture was agreed with stakeholders with a revision procedure supported by a second level ranking also involving economic and maintainability features. Following section provide a detailed

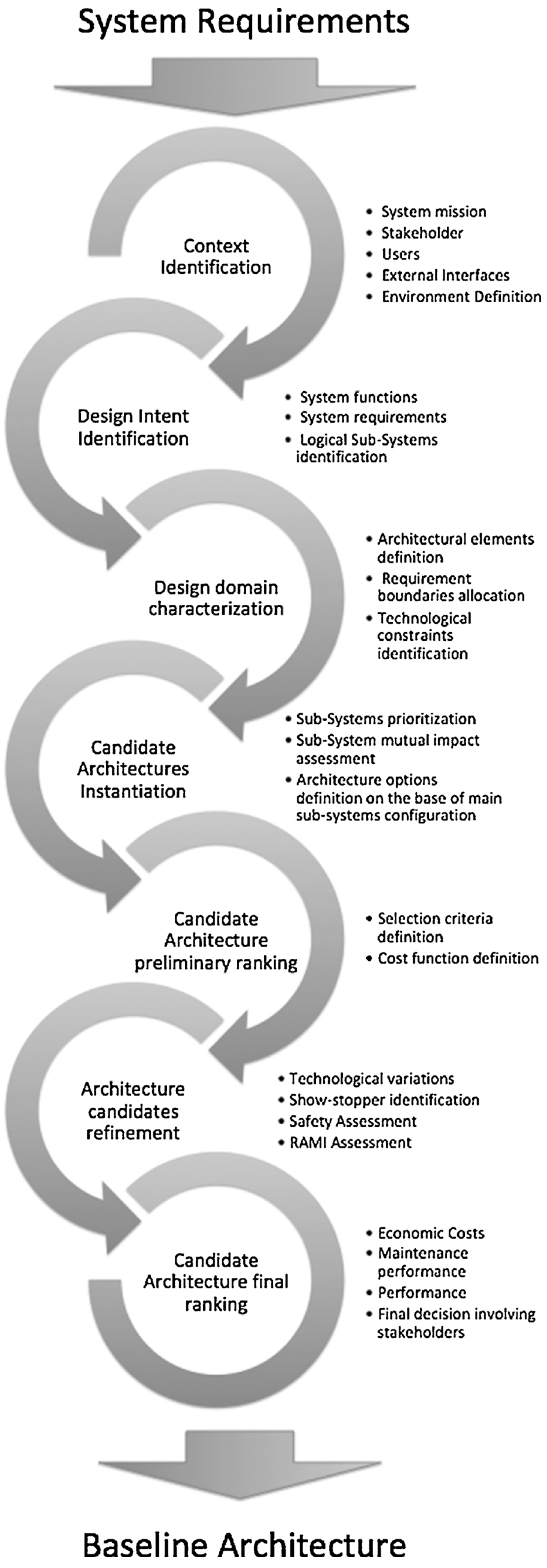

Fig. 3. Schematic representation of proposed methodology.

description of outlined process.

2. Design intents and system functions definition

The first phase is meant to capture design intents by means of the unbiased definition of system functions. Being a diagnostic, the system design driver was identified in the measurement specification provided from stakeholders, i.e. the emissivity profile measurement. Fig. 4 summarizes the RNC system context. As mentioned in the introduction, the RNC system is directly facing plasma located in the Vacuum Vessel (where nuclear fusion reactions occur). Plasma itself is an external system with which RNC system interacts both in terms of functional requirements related to the measurement to be performed and in terms of loads to be withstood or plasma environment not to perturb. Also other types of loads are defined and coming from surrounding systems/ environment, such as: mechanical, seismic, thermal, nuclear (mainly neutrons and γ rays) and electromagnetic.

The system is controlled by IO control system and a set of plant relevant parameters (radiological, fire, etc.) is monitored by devoted external system. To fulfill its measurements RNC system relies on the integration of other diagnostics data (e.g. plasma equilibrium data) and several auxiliary supplies (power, vacuum service, cooling water, etc.). Due to nuclear activation, system maintenance requires a Remote Handling system which is partially external, meaning that part of its tools are in the scope of RNC design even though constraint by interface requirements. Decommissioning implies interaction with decommissioning facility.

Among the stakeholders we mainly identify:

i F4E European agency, which is funding and supervising the design process and the system procurement. This stakeholder mainly impacts the design phase not providing user actors in operational phase.
ii IO, which plays a key role in defining design drivers and has the ownership of measurement requirements. This is relevant for negotiation of possible relaxation of expected performance under specific plasma scenarios. Moreover IO is the main responsible for system design reviews. Being the plant operator organization, it also provides two of the main user actors:
  - Operators interested in the RNC measurement for plasma advanced control during ITER operating phase.
  - Operators performing system maintenance and decommissioning operations
iii Safety Authority which is enforcing the operation within a safe domain in agreement with national laws as stated in the operating licence.

RNC system mission was defined according to measurement requirement identified as the main design driver: “To measure Neutron Emissivity Profile assuring minimal shutdown dose radiation behind port plug in the interspace area”. The main functions deriving from such mission were defined as:

1 To provide view of uncollided neutrons from a given poloidal section of plasma;
2 To detect particle/radiation;
3 To perform calibration;
4 To provide background minimization for measurement;
5 To perform data acquisition and processing;

Fig. 5 shows an example of how the functions hierarchical architecture tree was developed from the main functions above. Lower levels of function tree help understanding the related system logical and physical implementation as detailed in Section 2.1, e.g. the detection chain (routing, preamplification, etc.). The functions emerging from system mission are completed with auxiliary functions related to the

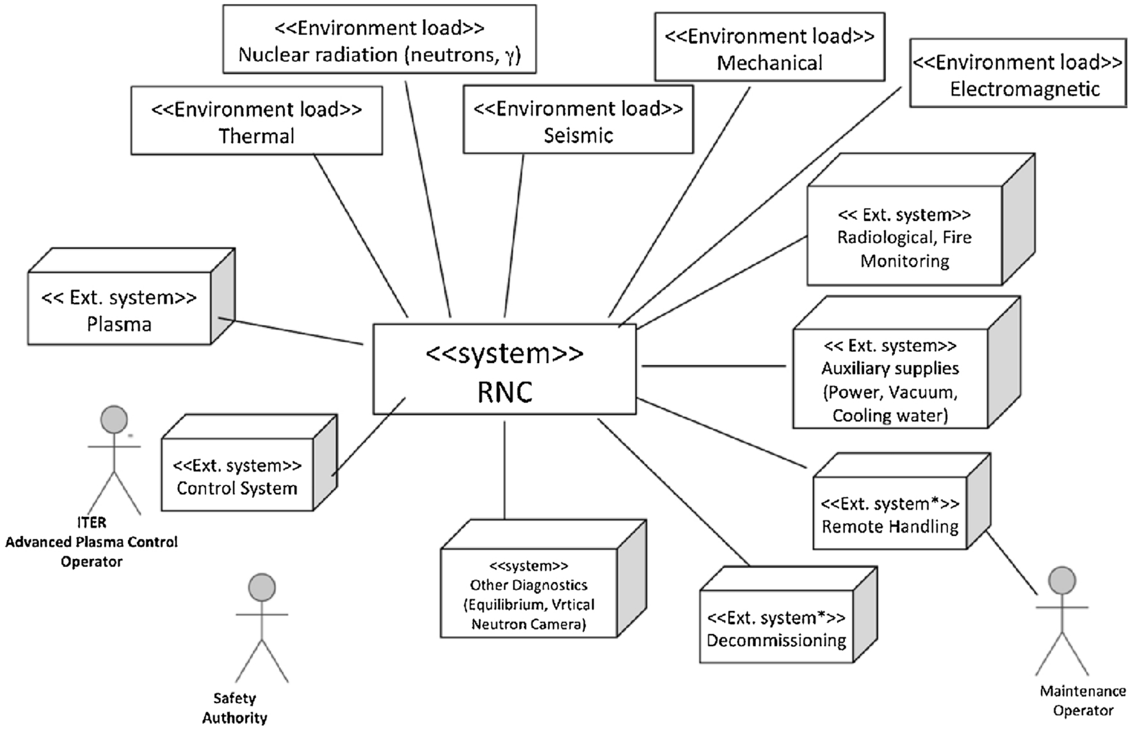

Fig. 4. RNC context diagram.

integration of RNC system into ITER Tokamak systems and the consequent functional requirements in terms of machine protection and nuclear safety. These functions are considered as placeholder motivating the design of specific sub-systems.

2.1. Architectural elements and system domain identification

According to ISO 15926 ontology is “A formal representation of a set of concepts within a domain and the relationships between those concepts”. Here we will exploit this approach with the purpose of capturing design intents, achieving a clear definition of RNC system architectural domain and a formal representation of RNC design space.

The identification of the baseline design concept hence implies the elicitation of design intents as well as the definition and assessment of architectural options spanning the design space [13]. An RNC architectural option was defined as an instance of RNC sub-systems configuration. As shown in Fig. 6, RNC sub-systems exist within architectural sub-spaces each defined by respective architectural elements, acting as base of such spaces. To form the base of architectural sub-spaces, such architectural elements are mutually independent and exhaustively covering the variability of the considered sub-space to the best of designer knowledge. So we can generalize Fig. 6 into Fig. 7 abstracting the RNC design architecture in terms of relevant design concepts, prioritized according to their perceived hierarchical structure (see Section

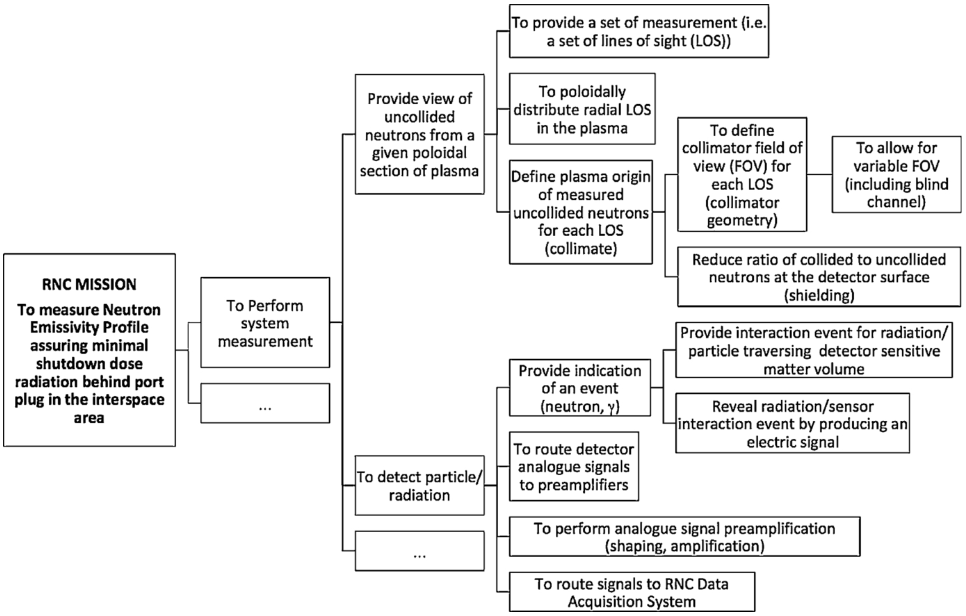

Fig. 5. Function tree hierarchical expansion: sample subset of functions for the system measurement mission.

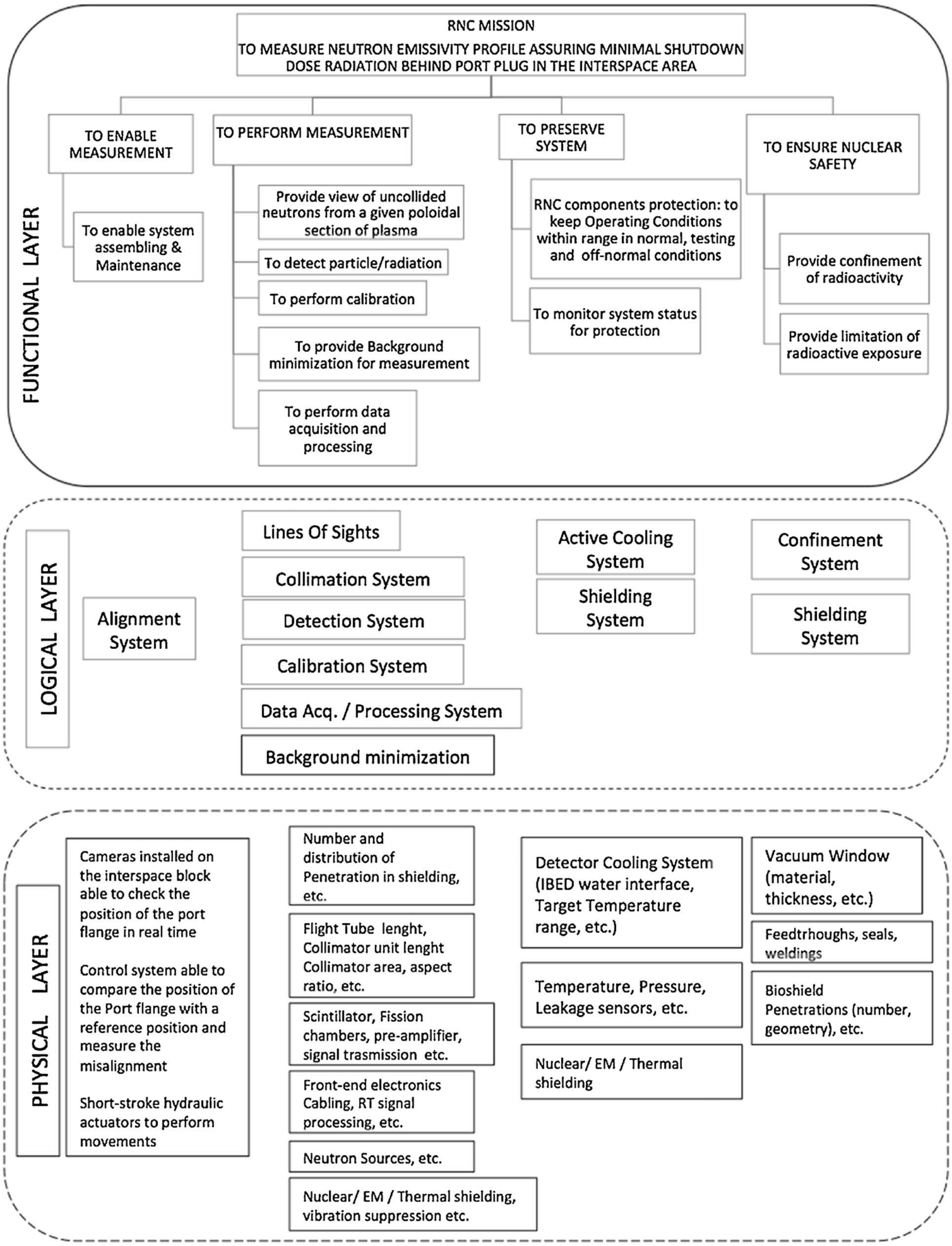

Fig. 6. Representation of RNC system in terms of functional, logical and physical layers. Logical layer enumerates sub-systems emerging from identified functions, while the physical layer is characterized by instances of architectural elements.

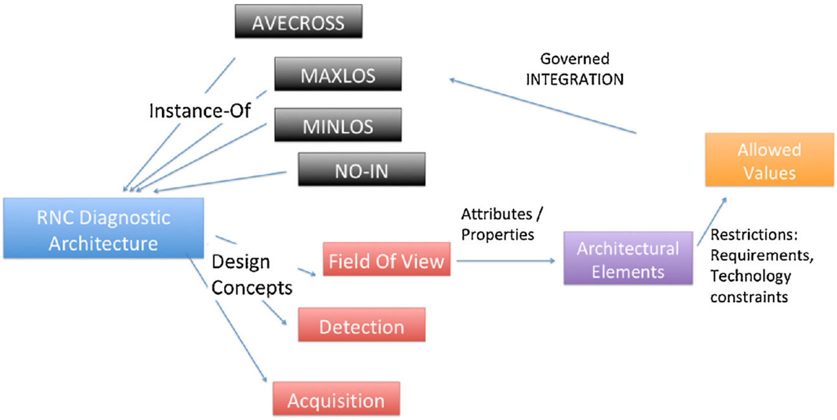

Fig. 7. Ontology defined as design working language for the architecture candidate instantiation.

Table 1
Example architectural elements and domain boundaries related to design driver concepts.

Design Concept: Plasma coverage Sub-system: LOS

Architectural Element	Boundary min	Boundary Max	Resolution Step
Number of LOS	10	30	5
r/a of edge LOS interceptions with plasma axis	0.6	0.9	0.1
In port angular spacing	Uniform spacing as the profile might be any. No optimization for any particular profile		
Ex port angular spacing	Uniform spacing as the profile might be any. No optimization for any particular profile		
In-Port LOS (Y/N)	Y	N	
Angular offset from radial plane	0	–	Little variability allowed
Number of in-port LOS crossing in the plasma with at least another line	0	8	4
Design Concept: Field of View Sub-system: Collimators			
Architectural Element	Boundary min	Boundary Max	Resolution Step
Flight tube Length (m).	2	4	1
Collimator units length (cm).***	25	80	20
Distance between LOS focus and front collimating unit.	0	2,6	–
Distance between Detector and back collimating unit (cm) ****	0	15	4 (0, 5, 10, 15)
Collimator area (front and back) (cmˆ2)	0,2	4*Pi	–
Collimator aspect ratio (ratio of vertical to horizontal dimension).	0,5	1	0,25

Table 2
Example of function, related architectural elements and domain for technology bounded sub-systems.

Design Concept: Particle/Radiation detection
Sub-system: Detection system

Architectural Element	Options
Detector Mix (combination of)	Diamond, Plastic Scintillator, Fission Chamber, GEM
Detectors number per line of sight	1, 2
Detector ordering along the line of sight	e.g. 1st FC, 2nd Diamond
Design Concept: Background Minimization Sub-system: Shielding/Insulation system	
Architectural Element	Options
Thermal loads	Active Cooling (Helium, Water) Thermal Shielding (Vacuum, Insulators)
Nuclear Shielding Block In-port	Stainless Steel + H20 Stainless Steel + B4C B4C TiH2
Nuclear Shielding Block In-port Beam Dump	B4C LiH CH2
EM Shielding	Cable shielding (ITER Catalogue)
Design Concept: Data acquisition and processing Sub-system: DAQ	
Architectural Element	Options
Sampling Rate/ADC resolution	250 Msamples/s-16 bit 400 Msamples/s-14 bit 1000 Msamples/s-12 bit
Real Time Spatial Inversion Type of algorithm	Tikhonov Neural Network Tomography
Fast Controller Architectures	PXIe ATCA
Design Concept: Calibration Sub-system: Calibration system	
Architectural Element	Options
Source	α-particle and ϒ-ray sources AmBe neutron source Active neutron source
Calibration Time	Usable for intershot calibration (min 107 n/s) within TMAX minutes
Calibration source position	Movable, Attached to detectors

2.2), specified by attributes/properties called "Architectural elements" which in turn can take a set of values restricted by requirements and technology constraints. This defines the adopted ontology to support domain exploration [14,15]. The governed integration process, which enables the instantiation of feasible architectural candidates, is described in Section 3.

The identification of architectural elements starts from the extraction of properties characterizing sub-systems to be designed. As an example Table 1 shows the architectural elements associated with the first design concept of "plasma coverage", emerging from function "Provide view of uncollided neutrons from a given poloidal section of plasma". The LOS sub-system is then defined mainly in terms of number and space distribution features/dimensions. Note that, due to higher environmental complexity of in-port location, also a Boolean variable Y/N for presence or not of in-port part was considered. After defining such features/dimensions, here called architectural elements, it is important to define the domain over which they can take values (e.g. number of in-port/ex-port LOS). These domain boundaries for architectural elements were derived from the set of available requirements and technological constraints. For example performance requirement asking for high accuracy ($< 10\%$) would push for higher number of LOS, while this number is constrained by the combined effect of limited available physical space for the RNC diagnostic (i.e. space boundary for the upper and lower LOS) and cross-talk effects across LOS which imply a minimal spacing across LOS. The resolution step (Table 1) defines the number of instances that will be generated by spanning the sub-space moving within boundaries: e.g. architecture instances considering 10, 15, 20, 25, 30 LOS. Without detailing the requirement management process, in the following we will assume such set of applicable requirements as available.

To avoid nonsense/forbidden architecture instances, boundary conditions were defined taking into account:

a) Project boundary conditions as defined by ITER requirements and/or design standards: constraints for equipment or configuration (e.g. space allocation, mechanical weight, etc.).
b) Technology constraints. As an example, available neutron detection technologies (Scintillator (Liquid/Plastic), Diamonds (D), Fission Chamber (FC), Gas Electron Multiplier (GEM)) were first assessed according to a set of functional properties: detection performance (sensitivity to 14 MeV and 2.5 MeV neutrons, energy resolving capability, spectroscopic capability; neutron/γ discrimination; flux working range, etc.); load withstanding performance (radiation

hardness, sensitivity to magnetic field, survival temperature, etc.); compatibility with in-port environment. Then the detectors technologies configuration/composition possibilities were adopted as architectural elements as reported in Table 2.

2.2. Sub-systems prioritization

Having defined in Section 2.1 the design domain space for each subsystem, one can propose configuration instances from such space. For example the LOS sub-system can consider an instance with no In-port section, 20 LOS, reaching 0.6 r/a coverage and 0 angular offset from radial plane. Similarly other instances for all defined sub-systems can be proposed hence obtaining a global instance for whole RNC system. In other words RNC system architectural space is obtained by union-merging of sub-spaces, so that the full system architecture instance can be expressed as a set of specific configurations of sub-systems.

The problem sudden arises to govern the instantiation process in order to obtain a *manageable* set of *feasible* architectural options still representative of the variety of the design space. The representativeness is needed to show to design reviewers that the eventually chosen baseline architecture results from an unbiased exploration of design space. “Manageable” is meant in terms of design effort to detail enough each solution so to enable its assessment (see Section 3). While for “feasible” we mean that, despite the boundaries of the sub-system space were derived from relevant applicable requirements, some sub-system configuration instances may not be mutually compatible in order to fulfill requirements. In other words despite eliminating clearly non-allowed architectures by taking into account project/technology constraints when defining boundaries, the integration of sub-systems can anyway result into RNC global-instances, which are not allowed (for example for safety reasons) or not feasible (for example for materials incompatibility). Therefore one needs to define a process to make the instantiation process efficient.

The approach adopted to govern the instantiation process was then based on functions/sub-systems prioritization according to two indexes accounting for complexity and mutual impact:

a) Complexity Index, determined as the product of sub-indexes (Table 3):
   i) Optimization complexity: number of constraints on parameters optimization;
   ii) Architectural elements complexity: number of parameters and variability;
   iii) Variation complexity:
      (1) impact on design driver in case of variations (1 to 5, with 5 representing the highest impact)
      (2) cost of late change (1–to 5, 5 the highest cost) [16,17];
   iv) Impact on other sub-systems, specifically the number of parameters of the other sub-system impacted from a variation in considered sub-system (Table 4). Assessing and achieving subsystem design decoupling or mutual independence is recognized as a key factor of successful design [18]. This point is widely addressed by several design methodology, above all by the axiomatic design, which focus on the design parameters decoupling as main driver for a successful design [5,9].

Table 4
Sub-systems mutual dependency. Note that the table assign a direction to impact (i.e. LOS impacts 1 COL parameter and vice versa).

	LOS	COL	DET	CAL	BACKG	DAQ
LOS	–	1			4	1
COL	1	–	1		1	1
DET			–	1	5	
CALIB				–		
BACKG					–	
DAQ		1				–

From the two indexes we can state that RNC system architecture candidate instances can be built by an ordered instantiation of the subsystems as in Table 3, meaning that first LOS system is defined, then COL, etc. eliminating incompatible instances configurations in the lower level sub-system. The information in Table 4 supports the optimization process, in the sense that for example CAL system is perceived as independent from other systems and can be therefore developed independently and left free for optimization, while other systems like BACKG are strictly dependent from other sub-systems proposed architectural solutions.

In particular on the base of proposed prioritization, RNC partial instances were built by first defining sub-system options for LOS, COL and DET systems and integrating just these three sub-systems. Then the RNC- global instances were finalized by definining and integrating best fitting options for remaining sub-systems (BACKG, DAQ). CAL system was not analysed in this phase, due to its independency. Fig. 8 presents the identified architectural options instances.

3. Baseline architecture identification

Having established a set of representative architectural options (Fig. 8), a systematic method to compare and rank them in order to select the best one was developed. The method ingredients are a set of selection criteria and a ranking function, which taking in input the scores associated to considered architectural options for each selection criteria, will provide in output a global score for each architecture.

3.1. Architecture selection metrics

Two main drivers guided the selection criteria definition:

a) Identify relevant aspect characterizing a generic RNC architectural option;
b) Define a measurable or quantifiable Figure of Merit (FOM) set that can be used to rank given architectural options;

Starting from these points the following fields were identified to characterize criteria:

Table 3
Prioritization of sub-systems. Lines of Sight(LOS), Collimators(COL), Detectors (DET), Calibration (CAL), Data Acquisition (DAQ), Background minimization (BACKG).

	Constraints on parameters Optimization	Parameters	Sum of the number of options per parameters	Relevance for Design Driver (1-5)	Cost of late Change (1-5)	Complexity Index
LOS	3	7	16	5	5	8400
COL	1	6	14	4	4	1344
DET	2	3	8	5	4	960
BACKG	2	5	15	2	3	900
DAQ	2	3	8	3	1	144
CALIB	1	3	5	3	2	90

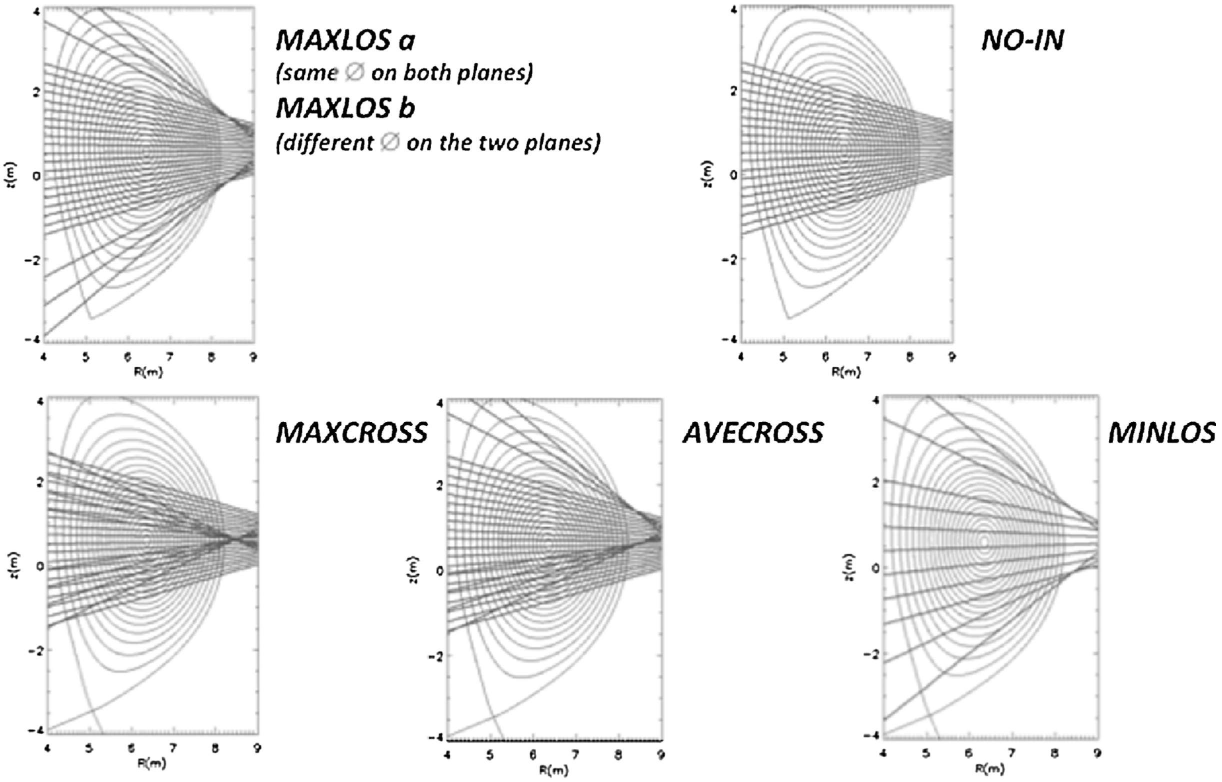

Fig. 8. Architectural options identified. Naming and representation is mainly based on field of view concept.

1) Selectivity Impact. This field may take the following values:
    - i) GO/NO-GO (G): a reference value (upper or lower limit) must be met for the architecture to be "accepted". Note that GO/NO-GO criteria, once met the requirement, also contribute to architecture ranking.
    - ii) RANKING (R): criterion just impacting the ranking of the architecture but not able to eliminate an architecture.
2) Weights: this field assign a weight to the criterion according to Analytic Hierarchy Process (AHP) [28–30] (see Section 3.2)
3) FOM scale: the scale interval over which FOM will take values.
4) FOM Requirement Baseline Level: the reference value used as baseline for FOM value.
5) FOM Requirement Type, e.g. "Upper limit" for the max shutdown dose rate.

The set of criteria adopted for architecture scoring is reported in Table 5.

3.2. Ranking function definition

The objective is to find a function able to put together in a consistent way the performance of each considered architecture option in the various selection criteria identified in Section 3.1 and consistently rank them [19]. The function then shall have the following characteristics:

1 Modularity, i.e. able to take simultaneously into account the impact of different independent selection criteria with different weights and having the possibility to add/remove criteria to have insight on their impact.
2 Linearity in response, monotonic in order to be easily interpretable.
3 Able to clearly identify a non-compliancy (“NO-GO”) condition, by becoming negative when a requirement criteria is not met.

According to specifications above, the following form has been chosen for the ranking function Sj.

$$\begin{aligned}&\text{module}(S_j) = \Sigma_i(W'_i C_i(A_j))\\&\text{Sign}(S_j) = \text{"e;} - \text{"e; if}(C_i(A_j)) < 0\\&\text{for at least one "e; GO} - \text{NOGO"e; } i - \text{th criterion}\end{aligned} \quad (2)$$

with Sj = Score for Architecture Aj, C_i = functional form, according to FOM type, for i-th selection criterion. The C_i functional forms per figure of merit type have been assigned in Table 5 and defined as:

a) Maximize or Minimize functional form: C(X) = x/L, where L is the Max(Aj score) or Min(Aj score) over available j architectures;
b) Upper Limit functional form: C(X) = - x/L + 1, where L is the Limit stated from requirement;

To define the weights w'_i associated to the i-th criterion score, a Pugh Matrix-like approach was adopted [20] and applied to rank criteria according to their relevance for the design driver measurement (see Table 6). To exemplify the way the ranking function operates, let’s considering the FOM number 5 in Table 5: “Average relative error in the reconstructed profile”. It is defined as relative error, so the scale is from 0 to 1.

Since the requirement is to have at most a 10% error over the entire r/a range, the FOM Req. field is 0.1 (i.e. 10%). The chosen functional form for FOM C_i field is of type “Upper Limit” with a limit of 0.1 stated above so, e.g. for architecture MAXLOSa the contribution of this FOM is $w'_5 C_5(A_{MAXLOSa}) = 0.07*(-0.09/0.1 + 1) = 0{,}00489$ given that:

a) Average relative error calculated from simulations for MAXLOSa: 0,0930
b) It is a GO-NO-GO criterion since associated to a requirement and MAXLOS is compliant since 0.0930 score is < 0.1.
c) Relative weight $w'_i = 0.07$ as deriving from Pugh Matrix (see Table 6) calculations.

Table 5
Selection criteria adopted for architectural scoring. DD and DT refer to Deuterium-Deterium or Deuterium Tritium reaction scenarios (See Section 1).

FOM #	Impact	Weight	Description	FOM Description	FOM scale	FOM Req.	FOM Requirement Type
1	R	0,085	Emissivity Dynamic Range, calculated as decades of emissivity covered, provided an accuracy of < 10% on whole profile.	max_on_reference_scenarios[log(max_on_r(Y(r)))] - min_on_reference_scenarios[log(min_on_r(Y(r)))]	0 - 5	4,77815125	Maximize
2	R	0,052	Emissivity Dynamic Range	average(max_on_reference_scenarios[log(max_on_r(Y(r)))] ; min_on_reference_scenarios[log(min_on_r(Y(r)))]) - average (log(6*10ˆ18);log(10ˆ14))	0 means exactely centered in required range	0	Minimize
3	R	0,034	DD/DT neutron separation (ex-port)	Capability of ex-port detectors to separate DD and DT neutrons	Only DD, only DT, DD and DT separated, DD and DT not separated (no spectroscopy)	DD and DT separated (1), only DT(2/3), DD and DT not separated (1/3), only DD (0)	Maximize
4	R	0,034	DD/DT neutron separation (in-port)	Capability of in-port detectors to separate DD and DT neutrons	Only DD, only DT, DD and DT separated, DD and DT not separated (no spectroscopy)	DD and DT separated (1), only DT(2/3), DD and DT not separated (1/3), only DD (0)	Maximize
5	G	0,07	Average (abs) relative error in the reconstructed profile over the entire r/a range (see condition "spatial range" in measurement requirements)	Accuracy	0 – 1	0,1	Upper Limit
6	G	0,28	Average (abs) relative error in the reconstructed profile over r/a < 0.85	Accuracy	0 – 1	0,1	Upper Limit
7	G	0,14	Global profile reconstruction accuracy estimate	Fraction of spatially reconstructed profile values whose relative error is below the required uncertainty.	0 – 1	1	Maximize
8	G	0,197	Spatial range covered	Maximum r/a achievable within required accuracy	0 – 1	0,8	Maximize
9	G	0,0216	Average (abs) relative error in the reconstructed profile over the entire r/a range (see condition "spatial range" in measurement requirements table)	Precision			Minimize
10	G	0,0864	Average (abs) relative error in the reconstructed profile over r/a < 0.85	Precision			Minimize

Table 6

Mutual relative importance assessed by means of mutual Pugh matrix. The relevance is stated with respect to design driver measurement.

	Emissivity Dynamic Range (Covered scale 10n)	Emissivity Dynamic Range Accuracy	DD/DT neutron separation	Average relative error in the reconstructed profile	Global profile reconstruction accuracy estimate	Spatial range covered	PRECISION
Emissivity Dynamic Range (Covered scale 10^n)	1	3	3	1/3	1/3	1/3	1/3
Emissivity Dynamic Range Accuracy		1	3	1/5	1/5	1/5	1/5
DD/DT neutron separation			1	1/3	1/3	1/3	1/3
Average relative error in the reconstructed profile				1	3	3	3
Global profile reconstruction accuracy estimate					1	1/3	3
Spatial range covered						1	3
PRECISION							1

3.3. Architecture candidates assessment and baseline architecture selection

In section 2.1 and 2.2 (Table 3) we have mentioned how some sub-systems are not driving the architectures instantiation process but are left free for optimization after higher-level sub-systems have been defined. So that after applying the ranking function to candidate architectures, each architecture candidate has an associated score mostly relative to first sub-systems (LOS, COL, DET). A refinement selection is then needed to achieve the baseline architecture option. This refinement has been performed in two steps. First candidate architectures have been detailed in terms of technological feasibility. For example the cooling technological implementation (helium vs water, operating pressure, etc.). Also each candidate architecture performance in terms of vacuum compatibility, safety /RAMI performance (by means of preliminary FMEA analysis [21–23]) has been assessed by experts in order to find possible show-stoppers, strength/weakness and possible risks. Then a second order ranking analysis has been performed taking into account also economic cost and maintenance indicators, which are relevant for the stakeholders (F4E and ITER) (see Fig. 4).

This refinement process is outlined in Fig. 9. In particular three separate rankings for the RNC architectural options have been produced for the following areas:

i) Performance: use of ranking function (Section 2.2) performance indicators derived from the analysis based on 1D neutron emissivity reconstruction analysis supported by a multi-criteria decision making technique (Analytic Hierarchy method) [24,25];

ii) Maintenance/Remote Handling: use of indicators and Analytic Hierarchy method. ;

iii) Economic Cost: a preliminary assessment of costs architecture candidate costs was performed, mainly defining a unit cost per LOS (including detectors) and other general costs for shielding and engineering design activities.

For maintainability, the Fuzzy-Analytic Hierarchy Process (F-AHP) has been adopted for comparative evaluation [24,26,27]. AHP has been proposed in literature as a methodology to deal with complex real-world multi-criteria decision analyses (MCDA) [28,29]. Since, in particular during the first stage of the design, decision makers' requirements may contain ambiguity and the human judgment on quality attributes may be imprecise [30], in this research AHP is used with a fuzzy approach, using triangular fuzzy numbers [24,27,31]. The Fuzzy-AHP has been widely used recently in complex MCDM problems [25,32] and its application in the conceptual design of tokamak components is discussed in [9,33]. Further details on the method are available in [5,34,35]. As prescribed by this methodology, at first some evaluation criteria have been selected and weighted by means of pairwise comparisons.

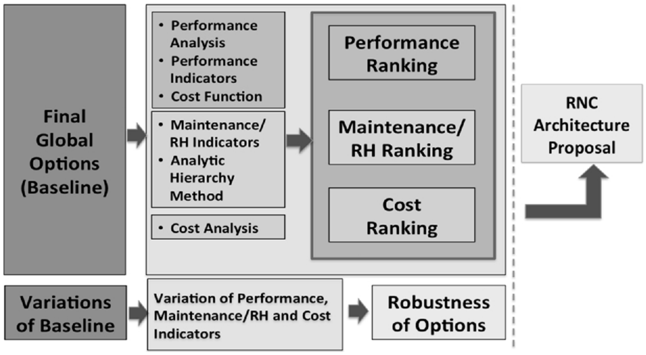

Fig. 9. Architectural options second level ranking.

The evaluation criteria, listed in Table 7, have been defined basing on the experience of the designers related to the impact of maintenance operations on design complexity and plant availability. Table 7 shows also the weights obtained for each criterion. At the second step, the 6 options have been pairwise compared against each criterion, obtaining the weights for each option related to each criterion (Table 8) and then the global weights (obtained considering the criteria weights, Table 9), representing the final score (Table 9, Fig. 10). As shown in Fig. 10 all the architectural options are roughly equivalent except for NOIN option, since this option has only ex-port equipment with the significant advantage of avoiding Remote Handling maintenance operations, thus minimizing maintenance time and costs.

Finally each Architectural Option has been assigned an overall score, normalized to best architecture for each sub-category as reported in Table 10. Note that the highest the better: highest performance, less maintenance/RH, less cost. To investigate robustness of architectural options with respect to technological risks (e.g. exclude in-port cooling, only FC in in-port detection system, different shielding materials), variations on the baseline values have been also defined.

To better understand the concept of variation within an architecture instance, consider for example the RNC architectural option MAXLOSa (Fig. 8). For this architectural option, as far as the Cooling Design Variable is concerned, a cooling system both for the ex-port and in-port detectors is foreseen. Three *variations* have been identified to deal with cost and complexity reduction: a) complete removal of any cooling system; b) presence of cooling only in the ex-port detectors; c) cooling in the ex-port and cooling in the in-port only during baking. In order to

Table 7

Evaluation Criteria. Legend Human Assisted (HA), Remote Handling(RH).

ID	CRITERIA	Criteria weights
C1	Maintenance tasks minimization	19,0%
C2	Symplicity of maintenance operations	6,0%
C3	HA operations impact on maintenance time	30,0%
C4	RH operations impact on maintenance time	12,0%
C5	minimize ratio RH/HA	33,0%

Table 8
Relative weights.

	MAXLOSa	MAXLOSb	MINLOS	AVECROSS	MAXCROSS	NOIN
C1	16,8%	16,8%	15,5%	16,7%	16,8%	17,4%
C2	9,8%	9,8%	33,9	9,8%	9,8%	26,7%
C3	20,6%	20,6%	8,8%	20,6%	20,6	8,9%
C4	8,3%	8,3%	8,3%	8,3%	8,3%	58,3%
C5	7,1%	7,1%	7,1%	7,1%	7,1%	64,3%

Table 9
Global weights.

MAXLOSa	MAXLOSb	MINLOS	AVECROSS	MAXCROSS	NOIN
3,2%	3,2%	2,9%	3,2%	3,2%	3,3%
0,6%	0,6%	2,0%	0,6%	0,6%	1,6%
6,2%	6,2%	2,6%	6,2%	6,2%	2,7%
1,0%	1,0%	1,0%	1,0%	1,0%	7,0%
2,3%	2,3%	2,3%	2,3%	2,3%	21,2%
13,3%	13,3%	11,0%	13,3%	13,3%	35,8%

address the positive or negative impact of the *variations*, the corresponding % changes occurring in Performance, Maintenance/Remote Handling and Cost indicators have been determined (e.g. + 20%, -34%). Note that in general the Variations do not improve the Performance index of considered architectural option, since Performance index is mainly defined by (LOS, COL, DET) sub-systems configurations.

Final step in the process has been the definition of baseline architecture on the base of scores in Table 10 together with stakeholder who were hence put in condition to have insight on the sensitivity of ranking to variation of relative importance weight for performance, maintenance and costs (Table 10) and technology risks as addressed in the variations assessment. As a result of the proposed process consensus was reached together with stakeholders on the choise of MAXLOSa architecture as baseline proposal for RNC diagnostic.

4. Conclusion

A qualitative/quantitative methodology has been proposed for the identification of baseline architecture of a complex system. The presented case study is the neutronic nuclear fusion diagnostic RNC under design for ITER experiment. After initially capturing design intents by means of standard functional analysis, context definition and requirement analysis, these have been detailed and deeply clarified exploiting a structured exploration of design domain. In particular a base for design space has been defined and domain boundaries identified as emerging either from system requirements or from technology constraint. The system candidate architectures instantiation process has been formalized and guided by means of sub-systems importance and mutual impact analyses. The definition of a modular ranking function able to merge information from different categories has quantitatively supported the candidate options performance assessment.

The main added value provided by the proposed system engineering approach can be summarized by two keywords: integration and communication. The process of abstracting design architecture (Functions/ Systems with related behavior models) has provided practical support for the unbiased systematic integration and tracking of information. The effort put in defining design solutions for different sub-systems in terms of elemental variables has enforced a common framework for different experts (neutron physicist, signal processing, mechanical engineers) by disentangling implicit contribution of the various sub-systems (LOS, collimators, DAQ, shields, etc.) to RNC system global performance. Furthermore it has reduced the proliferation of hardly-integrable configurations, supporting designers at respecting time budget for baseline design proposal.

The design abstraction collaborative effort has also provided another, often underestimated, advantage: a clearer presentation of the reasoning behind design choices, which has simplified communication with stakeholders. Finally the use of hierarchical multi-step ranking has enabled the merging of information from different domains, such as economic cost or maintenance/ robustness considerations. This has allowed stakeholders to be proactively involved in the definition of best architectural option as baseline for next design phase, reducing the risk of late design changes or provider-client misunderstandings.

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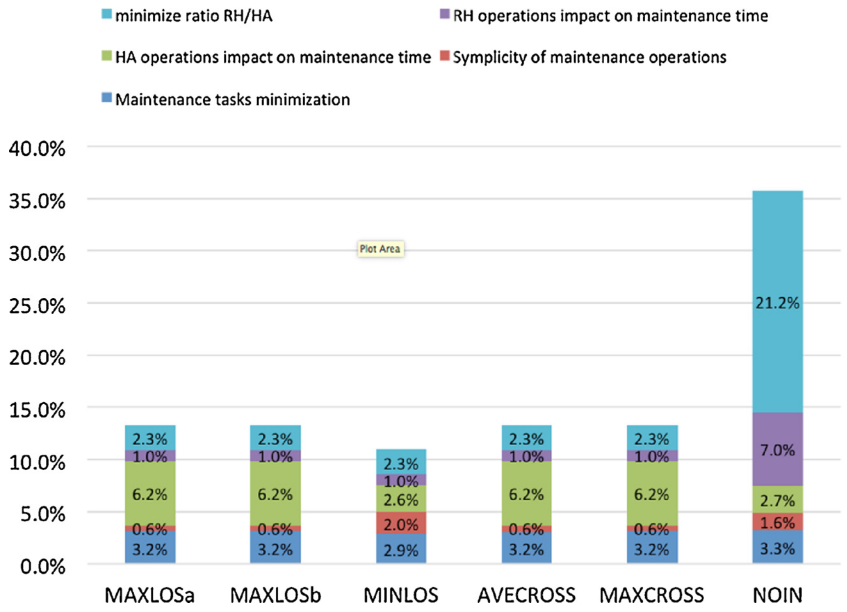

Fig. 10. Final score from maintenance perspective.

Table 10
Overall final score.

	MAXLOSa	MAXLOSb	MINLOS	AVECROSS	MAXCROSS	NOIN
Performance	91	50	72	100	21	6
Maintenance /RH	37	37	31	37	37	100
Costs	60	60	100	58	57	82

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