Requirements Engineering in complex systems design

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Abstract.
The realization of nuclear fusion reaction as energy source is under investigation, among the scientific community, through the design and development of tokamak reactors. Among the several experiments worldwide, the ITER project is the major international experiment and it involves several research institutes from several countries. In such a project, a Systems Engineering (SE) approach is requested to organize and manage the design due to its highly integrated design, the safety requirements related to nuclear aspects and the complex procurement scheme. The SE discipline focuses the attention on the requirements which are crucial for every successful project, defining what the stakeholders want from a potential new system, namely what the system must do to satisfy stakeholders need. Correctly stating WHAT is needed for the system, it is possible to obtain its conceptual design (HOW) as much as possible complying the requirements. The incorrect definition of requirements often leads to the failing of a project. Stakeholders' needs are written in Natural Language that is generally ambiguous, imprecise, incomplete and redundant. Their transformation into SMART requirements is crucial to avoid design failure. However, it requires a great expertise, unless a specific procedure is assessed. To this end, this work presents a specific procedure based on "like-mind" processes to make systematic the SMART requirements definition and assessment from stakeholders needs. The procedure is based on a demand/response framework and it is developed to obtain ITER requirements. However, it can be easily extended to every project using its own specifications. A specific case study on ITER Remote Handling is presented in this paper as example of the conceived requirements transformation procedure.

Keywords: Systems Engineering, Requirements Engineering, SMART Requirements, ITER tokamak.

1 Introduction

The development of innovative products requires a clear framework and tools to systematically deal with the concept design stage. In this design phase, the documentation and the traceability of design information play a main role for the development of a successful project and to avoid iterative re-design cycles, as well as to quickly explore many concepts determining those most likely to succeed. Systems Engineering (SE) discipline is widely recognized as the preferred mechanism for managing engineering activities in highly integrated environments. Both the international standard ISO/IEC 15288 [1] and the main Systems Engineering Handbooks (i.e. INCOSE Systems engineering handbook [2] , NASA Systems engineering handbook [3]) define the requirements elicitation activities as drivers for many of the system life cycle processes. Several research have demonstrated that successful projects depend on the correct definition of the needs and requirements of the customers and stakeholders from the beginning of the early design stages. Without establishing detailed requirements, the risk of project failure would be unacceptably high.

Requirement elicitation is an iterative activity and benefits from continuous communication and validation with the customer. No design can be completed before establishment of the System Requirements Documents (SRD) reflecting all relevant design inputs. Stakeholders' needs are written in Natural Language that is generally ambiguous, imprecise, incomplete and redundant. Their transformation into the so-called *SMART* requirements is crucial to avoid design failure. However, it requires a great expertise, unless a specific procedure is assessed. To this end, this paper presents a specific procedure based on "like-mind" processes to make systematic the SMART requirements definition and assessment from stakeholders needs. Such approach identifies the main activities to be followed to obtain SMART requirements even without expertise. The procedure is based on a demand/response framework and developed to obtain ITER requirements. However, it can be easily extended to every project using its own specifications. The advantages are mostly related to simplify the work, save time and make more effective the transformation procedure as well as the final requirements. In the next section a general overview on the requirements engineering will be provided. Then in Section 3 the conceived procedure is presented and it is then exemplified through a case study discussed in Section 4.

2 Materials and Methods

2.1 Systems Engineering discipline

SE is a methodical, disciplined approach for the design, realization and management (both operations and retirement) of a system [3]. A frequently used definition of a system is "a set of interrelated components working together toward some common objective", which implies a multiplicity of interacting parts that together perform a specific function [3]. SE is a holistic and integrative discipline, wherein the contributions of several engineering areas and many more disciplines are evaluated and balanced, to produce a coherent whole that represents homogeneously the different disciplines involved [5].

Among the various *Technical Processes* provided by SE, the *Stakeholder Requirements Definition Process* and the *Requirements Analysis Process* represent the crucial technical processes for the efficient development of a project, in particular during the conceptual design stage. Indeed, during the early design stage the requirements can be unclear, ambiguous and imprecise and they can be affected by lack of agreement among various stakeholders [5-7]. These situations are common at the early stage of the design process of complex systems, due to different experts involved in the collaborative design [8]. This work fits within these two technical processes aiming to provide a rigorous procedure for SMART requirements assessing from stakeholders' expectations.

2.2 Requirements engineering and SMART requirements

Requirements Engineering is a branch of Systems Engineering. It enables an agreed understanding between stakeholders, allowing the system's implementation and providing a basis of verifying designs and accepting solutions. Thus, requirements engineering is where the informal meets the formal [9].

The requirement should state "what" is needed, not "how". It means that in the earlier stage of *Stakeholders' Requirements Definition Processes* the important issue consists in defining what the stakeholders' needs, leaving out the possible solution which makes satisfy specified needs. Giving a solution in this phase could only constrain the design phase. The real issue of the requirements engineering can be found in the formal specification of the requirements. Stakeholders' expectations (needs) are generically written in natural language and they require to be translated in more detailed and not ambiguous forms. The essential characteristics for requirements can be seen in the word *SMART*. *SMART* is an acronym representing criteria to write good requirements. The letters S and M indicate *Specific* and *Measurable* respectively. Regarding the other three letters, there is not a common criterion to define them. In this work it is followed the interpretation provided by Fusion for Energy[1] in [10] with which the letters A is for *Achievable*, R is for *Relevant* and T is for *Traceable*. Following these five aspects users should formulate an effective requirement without misleading.

A requirement must be ***Specific***, because it must address **only one** aspect/function of the system design or performance being concise and simple. It must be ***Measurable***, because any characteristic required have to be expressed objectively and quantitatively. A requirement must be objectively verifiable (by test, analysis, inspection, or demonstration) to prove compliance. A desired capability that cannot be objectively verified should be written as a design goal, not a requirement. A requirement must be ***Achievable***, because it must be technically achievable at affordable costs within the relevant schedule conditions. A requirement must be ***Relevant***, because it must be needed to solve a problem or achieve an objective. A requirement must be ***Traceable***, because each requirement must have a unique ID and parents-children's relations must be clear and easily identifiable. Thus, requirements without a parent are referred to as orphans and their inclusion in the whole project context shall be assessed. Furthermore, each requirement must be linked to the stakeholders' need.

The SMART requirements must be assessed with two important processes: the requirements validation and the requirements verification.

Requirement's validation confirms the completeness, the compatibility and the correctness of the requirements. Requirement's verification is the process of design

[1] Fusion for Energy (F4E) is the European Union's Joint Undertaking for ITER and the Development of Fusion Energy.

qualification and product's acceptance. Generally, the *verification plan* should be preliminary defined by the project team which should indicate the requirement verification method (test, demonstration, analysis or/and inspection).

3 Procedure for writing SMART Requirements

The main flowchart of the conceived procedure for writing SMART requirements is shown in Fig. 1. The aim of the work has been the highlighting of several steps taken during transformation processes in view of the extraction of a Unified Modeling Language (UML) Activity Diagram, which is described in the current section.
The UML is a general – purpose visual modeling language that is used to specify, visualize, construct, and document the artifacts of a system. It captures decisions and understanding about a system that must be constructed [11].
According to the presented flowchart it is possible to make systematic the SMART requirements writing process, which is usually committed to system engineers with great expertise. The aim of this work is mostly related to simplify the work, saving time and making more effective the procedure as well as the final requirements. The benchmark of this work is the F4E released Requirements Writing Guidelines [10].
The procedure focuses the main actions to follow depicted through the main flow chart in Fig. 1. Some of such actions, defined "*invocation action*", have several sublevels needed to explain the source action. The invocation action can be recognized from the rake present on bottom right of the box action. To any of the actions presented in the main flowchart, a sub-flowchart is associated reporting the passages to perform such specific action. For sake of brevity, in this work only the main flowchart and the flowchart for one of the invocation actions are reported and discussed.
The first action is the "*Discussion with the stakeholders*". In this stage the stakeholders describe needs, wants, desires, expectations concerning the stakeholders' project. Generally, the output of such level are the requirements guidelines and the set of needs. The action "*Define a glossary*" suggests to list and to define the terms concerning the project. Creating the glossary means adding semantic definitions and synonyms of added terms; assuring that all those persons involved in the project understand a word in the same way, avoiding misunderstandings and fuzziness of communication. The next tasks are "*Select a stakeholders' need to be transformed*" and "*Record the stakeholders' need in a requirements depository*". The user shall select a first need to be analyzed, and then he shall record both the selected need and the need's source in a work file (e.g. file.xlsx). It is extremely important that every requirement is always traceable as well as linked to the corresponding need.

The next action "*Understand the stakeholders 'need*" is an invocation action and it maps to a specific flowchart. It is a brain work: the user shall reach a clear understanding of the selected need, identifying what the system should perform according to the stakeholders 'need, identifying what the system should perform according to the stakeholders 'need, performing a syntactic analysis, resolving all unknown terms (e.g. technical terms). It is important to check the list of words because if there are some ambiguous terms, stakeholders' clarifications must be integrated. Thus, the selected requirement must be marked as "to be updated", the analysis must be stopped and the next requirement can be considered. Concluding this task, from the main flow chart, it can be seen that if the need does not require stakeholders' clarifications, it is possible to move to the next action: "*Passage from the stakeholders' need to n SMART Requirement candidates*". This is an invocation action as well, characterized by three sub-levels as depicted in Fig. 2. Each stakeholders' need can contain several information. However, each SMART requirement shall hold a single information or feature that the final system shall have or perform. As a consequence, the user shall identify several *atomic requirements* to consider one at time. The user shall identify if the need expressed by atomic requirement is indeed a requirement rather than a goal, or a possibility, or an intention as well. The goal means an aim or objective to achieve; it is less strong than a requirement, but it is good that the system will achieve the fixed goal. If the atomic requirement is defined as requirement, the user shall transform it into a SMART requirement candidate following the invocation action "*Transform the stakeholders' needs into the SMART requirement candidate".* That candidate will be indeed a SMART requirement after several checks. Now, from the main flow chart, the user shall follow the action *"Record the SMART requirement candidate/possibility/goal/intention into requirements' depository"* and continue to formulate the next stakeholders' need. Some needs will require some stakeholders' clarification, and just after that the user will be able to continue the analysis. When all stakeholders' needs become SMART requirement candidate, the user can follow the next two actions of main chart "*Select a SMART requirement candidate*" and "*Check SMART requirement candidate*". A procedure for checking the whole set of requirements is also provided and it will be discussed in separate works by authors.

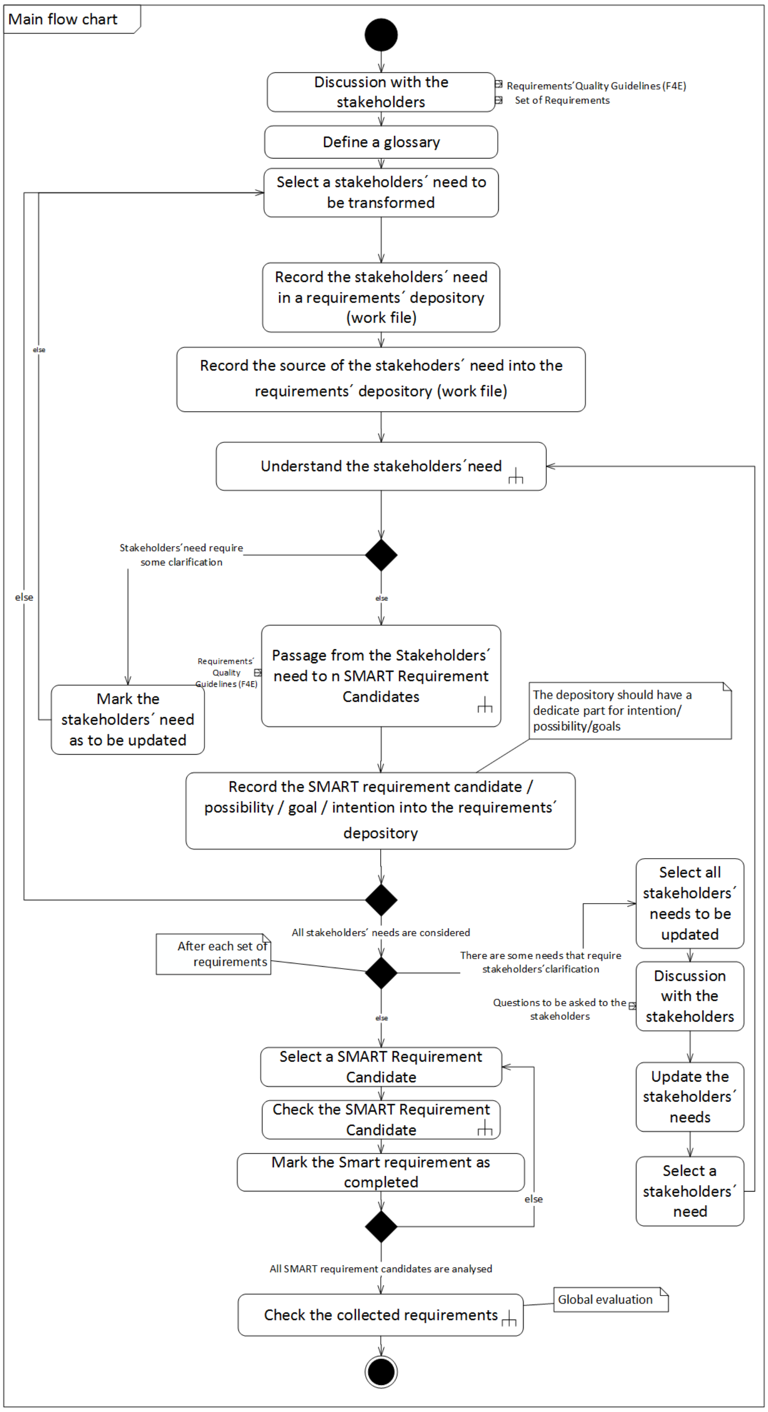

Fig. 1. Main flowchart for SMART requirements definition

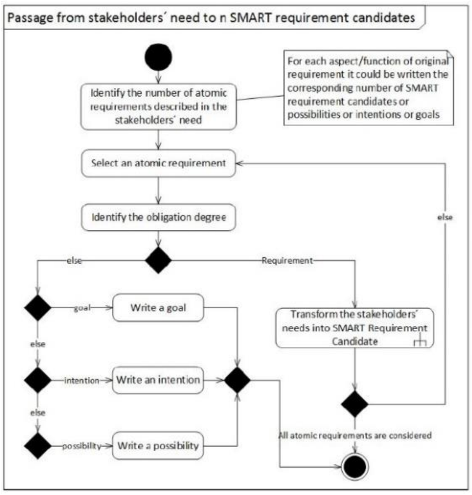

Fig. 2. Passage from the stakeholders' need to SMART Requirements

4 Case study: ITER Remote Handling Connector

The procedure has been applied to the requirements concerning the remote handling of a ITER component: the connector [12]. The connector is placed behind the divertor [13] cassettes, ensuring electrical energy to the diagnostic system mounted on the cassettes. The divertor area of ITER vacuum vessel consists of 54 modular cassettes, which must be replaced by means of Remote Handling equipment three times during the estimated 20 years of operation of the ITER. A clear representation of the connector location is depicted in Fig. 3. The connector must be uncoupled whenever the instrumented cassettes are removed from the ITER vessel. This would be done using a remote handling manipulator (MAM) and the tooling required for the connector operation should be minimal to simplify the deployment logistics. RH operations must be developed taking account the available space. To make easy the coupled (RH operation) between connector and cassette, the connector has three pins of different length and shape.

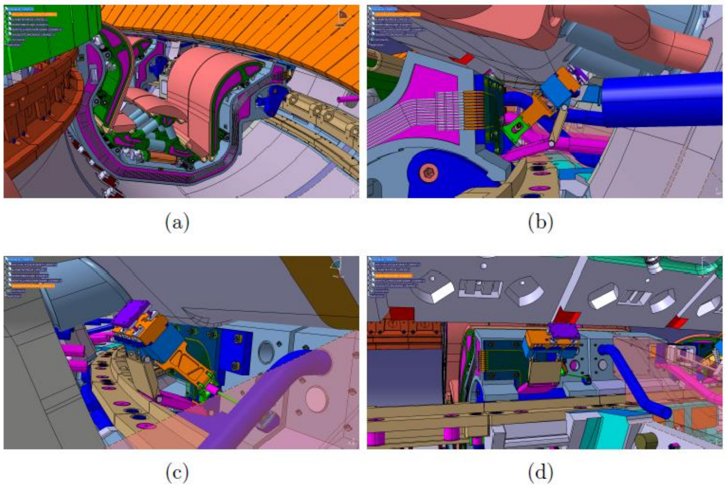

Fig. 3 (a) Divertor Cassette, (b) - (c) - (d) Connector behind the divertor

Ten stakeholders’ needs, concerning the RH connector, have been analysed and.transformed into SMART requirements, according to the procedure described in Section 3. For sake of brevity, two examples are reported below.

> STK.01 *"Electrical bonding shall be reliable and corrosion-free over the lifetime ofthe ITER installation, with no paint or any other insulating surface coating on bonded metal surfaces."*

Reading this stakeholders’ need, it is easy to notice that it refers to three different aspects of the electrical bonding: reliable, corrosion and surface coating.
Considering that every requirement has to be specific, namely it must address only to one aspect/function of the system design/performance, for each aspect must be written a requirement. After that, it is important to make these three aspects measurable. So, the reliability has been expressed using failure for time and the corrosion free using the corrosion velocity, obtaining the three following **SMART requirements**:
REQ1. The electrical bonding must have a failure rate not greater than λ^2.
REQ2. The electrical bonding must have the corrosion velocity less than Y over the lifetime of the ITER installation (excluding disposal stage).
REQ3. The electrical bonding must have metal surface without paint or any other insulating surface.

> STK.05 "*Pickling is rarely specified for vacuum components, normally only for those to be used in rough vacuum, since the process attacks the metal surface and the oxide layer, tending to leave residues which are difficult to remove.”*

SMART Requirement:
REQ4. If the pressure is less than 3×10^3 Pa the vacuum components must not have pickling as surface treatment.

REQ5. The vacuum components used in rough vacuum ($1x10^5$ to $3x10^3$) may have the pickling as surface treatment. (POSSIBILITY)

From several stakeholders' need it is possible to obtain the rationales and comments for SMART requirements, which are collected with the requirement itself.

5 Conclusions

In this work, a specific procedure for SMART requirements definition based on several "like-mind" processes has been presented. The aim is to make systematic the process of SMART requirements assessment and definition, saving time and reducing the required knowledge. It indeed can support users with no great expertise in systems engineering and requirement engineering. In this context, a specific tool has been designed in all parts looking at the many human processes made during requirement assessment. This procedure has been developed within ITER project and thus allows to obtain the requirements as required by ITER. However, changing the templates used and few particular requests (e.g. cross referencing, the use of particular modal verbs), it can be extended to every project. One of the main advantages introduced by this procedure is related to the unifying of the language used in the requirements' document, giving to every person that works at the same project the same understanding degree. On the other side, it should be noted that the process of requirements generation can be affected by variabilities and uncertainties depending on the type of project, so the proposed procedure should be verified in several different contest to be improved in its flexibility and robustness.
The implementation of a software supporting the user will allow to rapidly make SMART the stakeholders' needs. The software can be simply implemented following the flow chart and it is based on a demand/response framework.

Acknowledgments its flexibility and robustness.

Authors would like to express their sincere appreciation to E. Manda and the team of VTT Technical research Centre of Finland – Tampere for their contribution to this work.

References

1. Arnold, S,. Iso 15288 systems engineering—system life cycle processes. International Standards Organisation, (2002)
2. Haskins, C., Forsberg, K., Krueger, M., Walden, D. & Hamelin, D., Systems engineering handbook: INCOSE, (2006)
3. Kapurch, Stephen J., ed. NASA systems engineering handbook. Diane Publishing, (2010).
4. Kossiakoff, A., Sweet, W.N., Seymour, S. & Biemer, S.M., Systems engineering principles and practice, John Wiley & Sons, (2011)

5. Marzullo, D., Di Gironimo, G., Dongiovanni, D. N., Lanzotti, A., Mozzillo, R., & Tarallo, A., Iterative and Participative Axiomatic Design Process to Improve Conceptual Design of Large-Scale Engineering Systems. In International Conference on Design, Simulation, Manufacturing: The Innovation Exchange (pp. 492-505). Springer, Cham. (2019)
6. Di Gironimo, G., Lanzotti, A., Marzullo, D., Esposito, G., Carfora, D., & Siuko, M., Iterative and Participative Axiomatic Design Process in complex mechanical assemblies: case study on fusion engineering. International Journal on Interactive Design and Manufacturing (IJIDeM), 9(4), 325-338, (2015)
7. Legardeur, J., Boujut, J.F. & Tiger, H., Lessons learned from an empirical study of the early design phases of an unfulfilled innovation. Research in Engineering Design, 21 (4), 249-262 (2010)
8. Marzullo, D., Bachmann, C., Coccorese, D., Di Gironimo, G., Mazzone, G., & You, J. H., Systems engineering approach for pre-conceptual design of DEMO divertor cassette. Fusion Engineering and Design, 124, 649-654, (2017)
9. Hull, E., Jacson, K., Dick, H., Requirements Engineering, Springer, (2010)
10. (private communication) Serra,G., Requirements Writing Guidelines, (2012)
11. Rumbaugh,J., Jacobson, I., Booch, G., The Unified Modeling Language Reference Manual, Second Edition, Addison-Wesley, (2004)
12. Lyytinen, Janne, et al. "Development of the remote handling connector for ITER divertor diagnostic system." Fusion Engineering and Design 165: 112243, (2021)
13. Marzullo, D., Bachmann, C., Coccorese, D., Di Gironimo, G., Frosi, P., Mazzone, G., & You, J. H., Progress in the pre-conceptual CAD engineering of European DEMO divertor cassette. Fusion Engineering and Design, 146, 942-945, (2019)