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Early lessons from the application of Systems Engineering at UKAEA

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Early lessons from the application of Systems Engineering at UKAEA (May 2017)

Dan Wolff, Richard Brown, Paul Curson, Rob Ellis, Tanya Galliara, Matt Harris

Abstract— **UKAEA have been applying Systems Engineering for several years, it has provided a unique perspective from which to solve complex engineering challenges, bringing together insights from all aspects and disciplines involved. Fundamental functional requirements of the systems have been captured and used to develop "solution agnostic" designs (or architecture) of each system at the highest functional level. This has allowed existing preconceptions of the design to be challenged and alternatives solution to be assessed against the abstract system architecture. Systems Engineering has also provided a rigorous methodology for recording and tracing the system requirements and associated designs down through multiple hierarchical levels. This paper presents the lessons learnt and the benefits seen from applying Systems Engineering at UKAEA. It presents case-studies from the European DEMO, both in the overall design and integration of the power plant as well as within specific work packages. It shows how the top-level work has produced a new perspective on the power plant design. In the work packages of remote maintenance & breeder blankets it discusses how functional preconceptions and assumptions have been challenged leading to improved designs. It also draws on the experience RACE (UKAEA) have gained from applying Systems Engineering to create an optimized design for the European Spallation Source Active Cells project. We identify the aspects of Systems Engineering which have been applied to greatest effect and consider both the short-term benefits already realized and the long-term benefits that are anticipated in the future.**

Index Terms— **Breeder Blanket, Nuclear Fusion, Power plant, Remote Maintenance, Requirements, System Architecture, Systems Engineering**

I. Background

As early as 2006 a Systems Engineering approach has been advocated on Fusion projects such as ITER [1]. However, in its application the emphasis has been on the breakdown of a physical architecture into sub-systems and management of the arising interfaces, as can be seen in [2] Logical / functional architecture design is not evident at the plant level. In the area of plasma control, Model Based Systems Engineering (MBSE) has been used, fruitfully employing the SysML language to develop the design of the ITER plasma control system [3]. Domain Specific Languages (DSL) such as M&C ML [4] have also been developed to enable detailed design and realization of monitoring and control systems in a consistent manner.

It is clear from the ITER Organization (IO) 2015 Annual Report [5] that the application of plant wide Systems Engineering for ITER is still a work in progress. In 2015 IO reintroduced a strong Central Integration Office with a key project wide function to "control and implement robust Systems Engineering and configuration management for ITER.". Whilst ITER's business units were working "to promulgate a common Systems Engineering culture".

Within the context of DEMO, which is the primary focus of the case studies in this paper, it has been agreed for some time that a Systems Engineering approach must be developed and adopted to deal with the level of complexity and uncertainty involved [6,7]. It is acknowledged that the sub-systems of DEMO cannot be meaningfully developed in isolation, but rather that designs should be considered within the context of an overall DEMO Plant Architecture Model (PAM). The importance of investigating multiple design points during this pre-conceptual design phase has also been stressed.

The results obtained from the PROCESS system code [8], have provided important inputs to the architectural development of DEMO. The simple models of the reactor systems contained within PROCESS have enabled an exploration of the design space of DEMO in terms of economic and engineering feasibility.

A methodology for applying aspects of Systems Engineering to the design of nuclear systems, focusing on the functional analysis and functional architecture was proposed by T. Pinna et al. [9]. As with the primary Systems Engineering work in evidence for ITER [3,4] the work presented in [9] applies the methodology to system control. T. Pinna et al. found the approach to be useful for the design of complex systems such as fusion reactors and recommended its application to the design of all DEMO systems.

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Within the Remote Maintenance work package of the European DEMO a particular emphasis has been placed on the use of Systems Engineering [10]. The impact this has had on the work being carried out by RACE / UKAEA will be covered later in this paper. However it has also led other associations to implement Systems Engineering practices. G. Di Gironimo et al. [11] adopted a Systems Engineering approach to the concept design of the DEMO divertor cassette-to-vacuum vessel locking system. Their work focused on developing designs in an incomplete requirements environment, proposing an Iterative and Participative Axiomatic Design Process (IPADeP). Their approach involved comparing candidate designs based on three very high level customer needs. In the absence of agreed user requirements, it relied heavily on expert opinion to establish the weighting of the customer needs and the rating of each design against those needs. The work presented by G. Di Gironimo et al. only covered the first iteration in their proposed process from which they intended to improve the definition of the requirements before iterating the design further. Fundamentally their approach seeks to develop requirements and designs for a relatively small sub-system in the absence of higher level requirements rather than to address the absence of top level requirements directly and cascade down from them.

The IPADeP approach was further adopted for the pre-conceptual design of the European DEMO divertor cassette [12]. In this work the design options for a divertor were developed within a prescribed geometric space envelope. Some 'high-level design requirements' are stated, which are phrased similar to the customer needs of [11]. There is no mention in [12] of a functional analysis or model of the divertor system, nor a characterization of the boundaries of the divertor system. In [12] the focus is on pairwise comparison of design aspects of the DEMO divertor by experts. Each aspect appears to be considered in isolation, not considering any interplay between the sub-systems of the divertor.

Within this landscape, UKAEA are seeking to employ a holistic Systems Engineering approach from the plant level down. We are bringing together insights from all aspects and disciplines involved to fully characterize the needs and constraints and then exploring the design space, starting from a functional, solution agnostic architecture. This work is being carried out using industry standard approaches [13- 16] to rigorously record and trace the system requirements and associated design choices down through multiple hierarchical levels with associated acceptance tests. Ultimately these tests will ensure that the fully commissioned system adheres to both the fundamental requirements as well as the chosen sub-system design solutions.

II. SYSTEMS ENGINEERING

A. Overview

Before we explore how Systems Engineering is being applied at UKAEA it is worth first considering what we mean by Systems Engineering. Whilst Systems Engineering is a widely recognized discipline, the way it is defined and applied can vary between different industries.

The authors of this paper are seeking to apply Systems Engineering in accordance with the principles established by the International Council On Systems Engineering (INCOSE) [13-15] and further captured in ISO/IEC/IEEE 15288 [16]. INCOSE defines Systems Engineering as "an interdisciplinary approach and means to enable the realization of successful systems." Fundamental to this approach is "System Thinking", a framework for seeing interrelationships rather than things, for seeing patterns rather than static snapshots. It integrates the people, purpose, process and performance of the system by drawing on physical and social sciences, engineering and management principles.

In more practical terms the key Systems Engineering activities can be summarized in the V lifecycle model fig. 1.

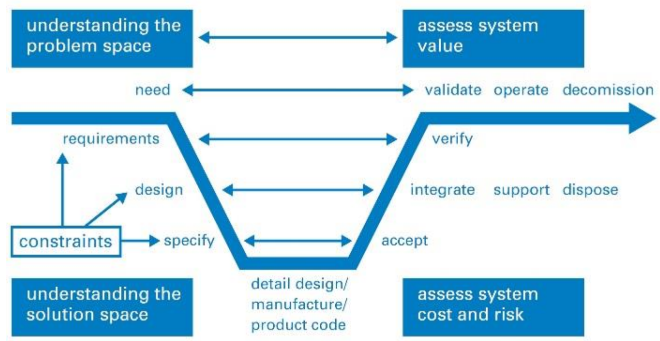

Fig. 1. V lifecycle model [14] showing the logical relationship between the different Systems Engineering activities.

The key steps followed in the application of a full Systems Engineering process [13] are:

1. Understand the problem
   - Identify key measures of operational effectiveness
   - Identify stakeholders
   - Agree the system boundary
2. Agree and manage the requirements
   - Requirements form the basis for contracts and acceptance. These should consider the desired effect of the new system and balance the requirements with budget and technical feasibility.
   - Relevant Stakeholders must be identified and consulted
   - Assumptions must be captured and identified
   - The impact of proposed changes must be considered and reviewed via trade-off studies.
   - The system must be tested against its requirements.
3. Investigate alternative solutions
   - Define a function design or architecture that characterizes the whole system
   - Consider, model and evaluate both novel solutions and improvements to the existing system
   - Work out how to choose between the alternatives
   - Record decisions made
4. Agree and manage the interfaces

   This allows teams to work in parallel, with the full confidence that all the pieces they are developing will fit together and work together. There must be a responsible owner for each interface.

5. Prepare the test and support systems
   Prepare the test, training and support capabilities in parallel with the 'operational' system: these need to be compatible and ready to use with the system when needed.

In some instances, UKAEA are applying Model Based Systems Engineering (MBSE). MBSE is the formalized application of modelling to support System requirements, Analysis, Design and Verification & Validation activities [13]. This approach moves away from a traditional document-based approach with information scattered between many sources. MBSE seeks to develop a single point of reference in a system model or set of models. The connected nature of the model(s) means it is possible to automatically query or verify it in ways too complex or otherwise impractical by manual inspection.

B. Application in UKAEA

Within UKAEA steps have been taken to determine how best to apply Systems Engineering principles to our work. Experience was gained on the MAST Upgrade [17] which identified that, in order to maximize the chances of success:

- Clear user requirements must be captured and cascaded to lower level systems.
- Efficient optioneering processes should be implemented to quickly agree the optimum balance between performance, simplicity, reliability & cost.

A formal internal process for the application of Systems Engineering within UKAEA is still under development. However, the emphasis is on a scalable approach, applying industry standard techniques as advocated by INCOSE [13-15] and ISO/IEC/IEEE [16]. A core Systems Engineering principle is that on smaller projects, Systems Engineering activities can be conducted very informally. On larger projects, increased formality can significantly help in achieving project opportunities and in mitigating project risk. Thoughtful tailoring and intelligent application of Systems Engineering processes are essential to achieving a balance between the risk of missing objectives and process paralysis [13].

The decision as to when to apply MBSE is also assessed on a project by project basis. When applying MBSE, UKAEA's modelling language of choice is SysML [18].

In terms of software tools, UKAEA carry out formal requirements management using IBM Rational DOORS and MBSE is primarily carried out using Sparx Systems Enterprise Architect.

III. CASE STUDY 1: DEMO PLANT LEVEL DESIGN & INTEGRATION

A. Context Overview

DEMO is a demonstration Nuclear Fusion Power plant and as such has a different design basis when compared to all the Fusion experiments which precede it. The mission of Fusion experiments has primarily been to develop our understanding and technology. The mission of DEMO is to integrate this understanding and technology into a Power plant which delivers electricity to a power transmission network. As a member of the EUROfusion consortium [19], UKAEA is working closely with EUROfusion Programme Management Unit (PMU), to facilitate this plant level design and integration in a structured, traceable and rigorous way.

B. Application of Systems Engineering

The engineering strategy adopted by the DEMO programme is to use a Systems Engineering approach to the development of the system [6,7]. The Systems Engineering approach adopted was the version defined by ISO/IEC/IEEE 15288:2015 [16]. The approach defines a path from stakeholder requirements through system requirements and design, using a requirements-led design philosophy. For complex systems like DEMO, the design process is used to split the system into sub-systems and iterate the requirements-design process for each sub-system. To that end, a top-level system design process has been adopted to define the set of sub-systems which comprise the DEMO Plant (referred to as DEMO systems). These systems can then form the focus of requirements development at the level below the Plant System and its Plant Requirements Document (PRD).

A key principle of the adopted approach is to split the design process into two layers; System Architecture and System Design, as shown in fig. 2 below.

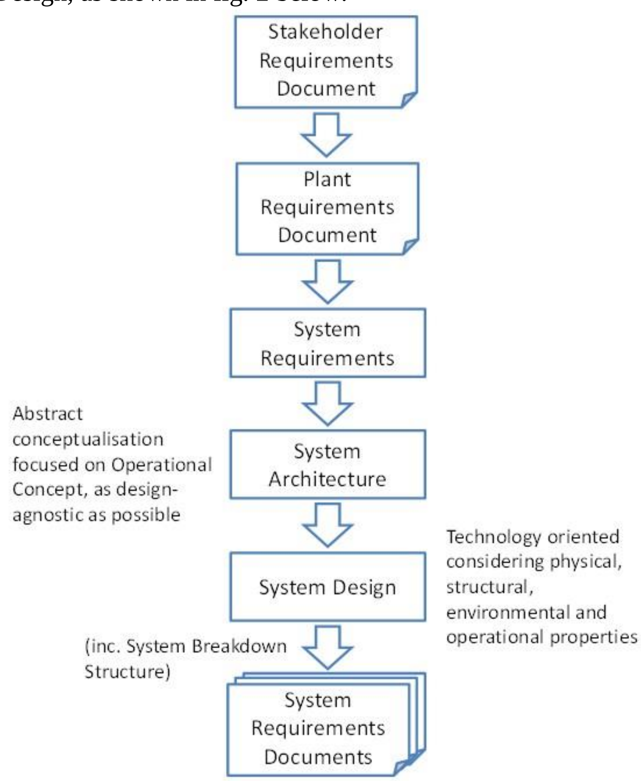

Fig. 2. Systems Engineering design process in the context of DEMO highlighting the difference between System Architecture & System Design.

The System Architecture defines a representation of the system as an abstract set of sub-systems, each defining the key behaviors and functions of the system, together with their properties and performance parameters.

Once the System Architecture is defined, the System Design process seeks to allocate actual system elements to the

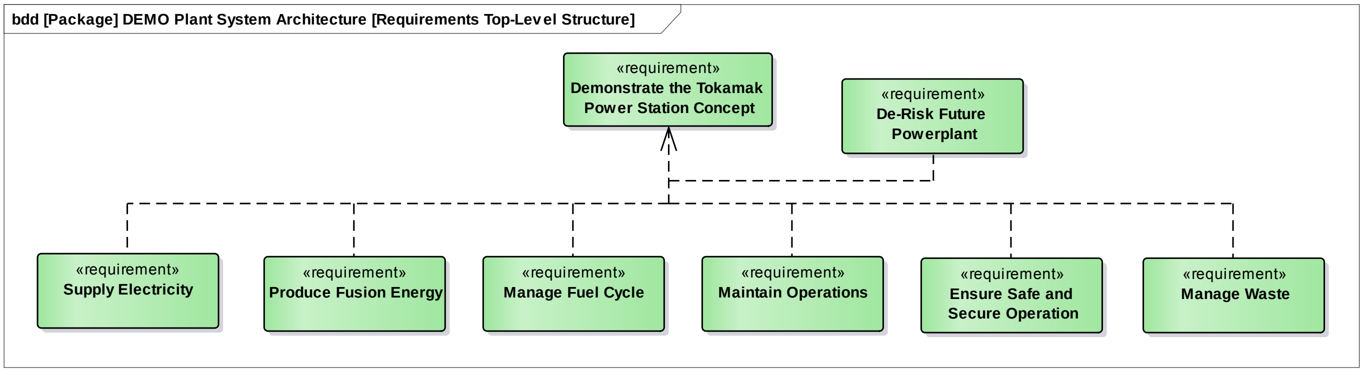

Fig. 3. DEMO plant top level requirements hierarchy from SysML DEMO architecture.

architectural entities and functions that they have defined. One of the aims of the System Design process is to define the System Breakdown Structure below the plant level, identifying the systems which comprise the plant as a whole.

It is tempting to jump straight to a Systems Design, particularly where there is a strong existing candidate design for a system. However, skipping the System Architecture compromises the ability to optimize the design and challenge pre-conceptions which may be ill-founded. In the DEMO context, the temptation is to base concepts blindly on ITER designs. Whilst we must certainly learn from the positive and negative experiences gained at ITER, not all designs will be appropriate for a Power plant.

The System Architecture Model provides a vehicle for facilitating discussion to explore the best options for the design of DEMO, making sure it aligns with the end goals of the project.

UKAEA are currently developing a System Architecture for DEMO written in SysML using Sparx Systems Enterprise Architect. This work is being carried out for EUROfusion in close collaboration with the fusion association across Europe, A key task is the Function Allocation for the Model. The existing work package structure for the European DEMO was targeted at the key technical challenges which must be overcome, therefore it does not always reflect the core functions of a fusion Power plant. For example, Remote Maintenance (RM) is a key technical challenge of a higher-level Maintenance function, rather than a function in its own right. RM will be shaped by decisions made on how overall Maintenance should work for DEMO. The initial work carried out developing the SysML architecture model has allowed the functional decomposition of the plant system to be started, example outputs from the first draft can be seen in fig. 3 & 4.

UKAEA have been supporting EUROfusion PMU in developing the plant requirements for DEMO. This has been carried out in tandem with the development of the DEMO architecture model. Work is ongoing to ensure the structure of the requirements database reflects the architecture. UKAEA have championed the use of IBM Rational DOORS for capturing and managing the requirements on the DEMO project. We are working, with the other members of the EUROfusion consortium, towards bringing all requirements from the top-level stakeholder requirements to the lowest sub-system requirements into a common repository with full traceability.

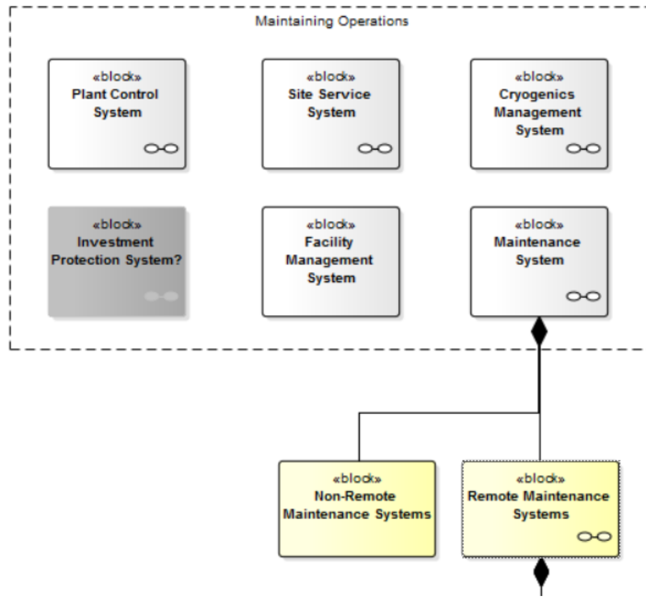

Fig. 4. Hierarchical breakdown of Maintain Operations function to functional sub-systems, from SysML DEMO architecture.

As important as capturing and linking the requirements is ensuring that those requirements are written to an acceptable standard. Key to this is ensuring that all requirements:

- Are placed upon the system of interest.
- Are specific and measurable so that it can be determined whether it has been achieved or not.

To this end we have been working with the Systems Engineering points of contact from across the European DEMO work packages. Workshops have been facilitated by EUROfusion where we have been able to share Systems Engineering best practice.

C. *Findings*

Given the potential scale of the DEMO project, the current pre-conceptual work has barely scratched the surface. However, it is at this early stage where the most cost effective analysis of different options can be carried out. It is therefore vital that we do all we can to facilitate this design space exploration, in order to ultimately minimize the cost to build and operate the tokamak and associated plant. The modelling carried out will allow different options to be explored quickly and cost effectively. By developing the System Architecture it provides a coherent functional framework to assess alternative designs against.

By beginning to capture and manage the requirements of DEMO within a database at this early stage we are placing the project in a good position from which to go forward. The rigorous recording and traceability of the requirements enables them to be interrogated to check for completeness and consistency. Preventing unnecessary duplication of functions and either low level requirements without a parent or high level requirements which are not being met at the low level. It also ensures that as the requirements evolve over the course of the project their change history is recorded and changes are cascaded to all areas affected. Furthermore, through this cascade it is possible to assess the impact of changes and therefore establish whether they are sufficiently beneficial or indeed feasible.

D. *Future Direction*

As previously alluded to there is still a substantial amount of work to be done to in the plant level design and integration of DEMO. The key work at this stage is to put in place the correct processes and tools to ensure that information is freely available to all on the project who need it. Therefore, completion of the first full System Architecture for DEMO is seen as key. Going hand in hand with this is the development and increased accessibility of the shared requirements database, with a structure which matches the architecture. Accessibility to the data needs to be accompanied by a shared understanding of how to use it. In this area, the Systems Engineering Points of Contact (SEPoCs) from across the European DEMO work packages will be key. They must act as a hub for spreading the Systems Engineering principles and methodology across the fusion associations working on DEMO.

An area which is becoming another key focus is interface management. NASA [20] states that management and control of interfaces is crucial to successful projects. Steps are being taken to ensure functional and physical compatibility among all interrelated system elements. The first stage is to capture, characterize and establish ownership of the known physical and functional interfaces.

IV. CASE STUDY 2: DEMO REMOTE MAINTENANCE

A. *Context Overview*

There is a broad scope of maintenance activities envisaged for DEMO which aren't foreseen as possible with manual 'hands on'. Therefore, the Remote Maintenance (RM) system of DEMO is wide ranging, interfacing with most other systems of the plant. The development of an effective and efficient RM system for DEMO is critical to maximizing the overall plant availability. This availability is one of the key factors that will determine the commercial viability of a fusion Power plant.

The RACE division of UKAEA is leading the pre-conceptual RM work package (WPRM) of DEMO. The aim of the current phase is to develop a maintenance strategy based on sound remote handling practice and technologies, relevant for a range of plant design options [10]. This strategy development is informed by knowledge gained from operating JET and design work for ITER. However, the framework in which the strategy is being developed is firmly based on Systems Engineering principles

B. *Application of Systems Engineering*

As with [11] & [12] RACE's DEMO RM team are operating in an incomplete requirements environment. In order to address this, we have engaged with all interfacing work packages to agree a draft set of requirements. These requirements are then captured and managed within IBM Rational DOORS. This dialogue has been extremely useful in ensuring that there is a common understanding between RM and interfacing work packages. In particular, we have been able to encourage the owners of systems such as diagnostics and magnets to think in terms of line replaceable units [21] when developing their designs. This approach, alongside building in sufficient redundancy will help us to achieve the required plant

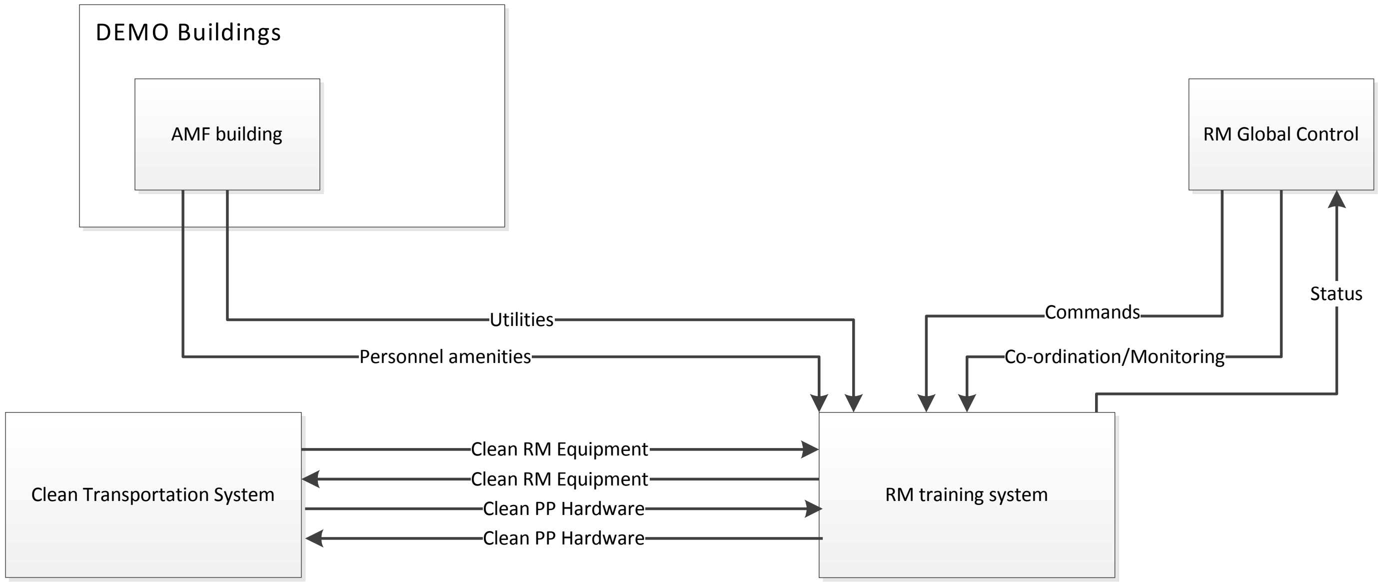

Fig. 5. Context Diagram of the Remote Maintenance Training System, showing all the Systems that it interfaces with and what flows between those systems.

availability figures.

Alongside the requirements work, functional modelling of the RM system has been carried out to better understand the system. Some modelling has been carried out using SysML formalisms, in Sparx Systems Enterprise Architect, to allow integration with the higher-level plant model mentioned in case study 1. However, the starting point for the modelling has generally been in simpler forms, starting with a team around a whiteboard. The collaborative nature to this first modelling step helps the whole team's understanding and allows knowledge to be shared at an early stage. A typical output from this first stage modelling can be seen in fig. 5.

Developing from the requirements and modelling work we are able to assess candidate design solutions for the various sub-systems of the RM system. In addition, we are evaluating the impact on RM of proposed changes to the DEMO plant design. One study of note investigated the impact on RM of varying the aspect ratio and number of TF coils for DEMO [22]. This work was instrumental in justifying the proposed change to the DEMO baseline from 18 TF coils to 16 TF coils.

C. *Findings*

Employing Systems Engineering to the DEMO RM system has been very helpful. The process of capturing and regularly reviewing requirements with interfacing work packages has instigated a dialogue which has benefited both sides. It has enabled challenges to the assumptions of what each system is capable of. Particularly around what maintenance of magnet systems will and won't be possible. Furthermore, it has allowed the scope and boundaries of the systems to be clarified and agreed upon. Through the formalized requirements management process involving the use of DOORS we have been able to preserve a hierarchically linked set of system and sub-system requirements, against which our design choices can be assessed. This will be invaluable as the project progresses.

Looking internally to the RM work package the functional modelling has been very valuable in helping to understand the 'solution agnostic' view of the RM system. It has enabled a focus on the overall role and function of the RM system and how this can most logically be divided into sub-systems.

D. *Future Direction*

A substantial amount of Systems Engineering information has been captured for the RM system primarily in the DOORS database but also as architectural models. However, owing to this work being carried out in parallel with the top-level DEMO plant design the linkages between these two datasets are not as strong as they could be. Therefore, a focus of current efforts is to ensure that the structure and linking of requirements and models from the DEMO plant down to the RM system is consistent with an agreed plant architecture.

The general tasks of developing the requirements and models will continue throughout the project in close collaboration with the owners of the interfacing systems. An area of focus for the coming year is to use MBSE to capture in a single place the key decisions that are made in the RM strategy. This will be linked to the relevant requirements and documents or other artefacts that provide substantiation for these choices. Alongside the chosen options will be details of other options which were considered and details of the assessment. This will be a powerful tool in justifying the course that has been chosen.

V. CASE STUDY 3: DEMO BREEDER BLANKET

A. *Context Overview*

The Breeder Blanket (BB) is one of the DEMO work packages.

It is a very significant system of interest for DEMO, with responsibility for, but not limited to, tritium production (for plasma fuel) and capturing useful thermal energy (for electricity production). It also acts as a shield against thermal & nuclear radiation, protecting the vacuum vessel and components outside the vessel, in particular the superconducting coils.

Four different BB concepts are under consideration for European DEMO, with the relevant technologies of each currently at a low technology readiness level.

The system design must overcome demanding challenges, including high neutron fluences and energies (up to 14MeV neutrons), high temperatures and thermal loads and be capable of being maintained remotely.

The Breeder Blanket System Requirements are partially developed, aimed at generic solution, but with few functional requirements identified.

B. *Application of Systems Engineering*

Over the past 12 months, a EUROfusion PMI task has been undertaken to establish a basic functional architecture for the Breeder Blanket, and the remote maintenance-breeder blanket interface. The work has been led by UKAEA, heavily supported by domain experts at KIT.

Stakeholder objectives for the work were captured in the form of a Stakeholder Benefits use case diagram.

A standard Systems Engineering approach has been applied, using the SysML language, with the aim of establishing a systems architecture for the Breeder Blanket comprising three levels: Functional Architecture, Logical Architecture, and Physical Architecture, see fig. 6.

The work has focused on developing the system operational concepts and the supporting functional architecture of the Breeding Blanket system.

The systems operational concepts developed comprise narrative and (use case) model descriptions of the Breeder Blanket context (from a behavioral perspective), and how the Breeder Blanket works internal to its boundaries. This serves to refine the system requirements, offering a mechanism for establishing completeness and consistency of the requirements specification.

The system operational concept description usually includes the operational goals, supporting scenarios required to be performed by the system and associated system lifecycle concepts.

A functional architecture has been partially developed, and

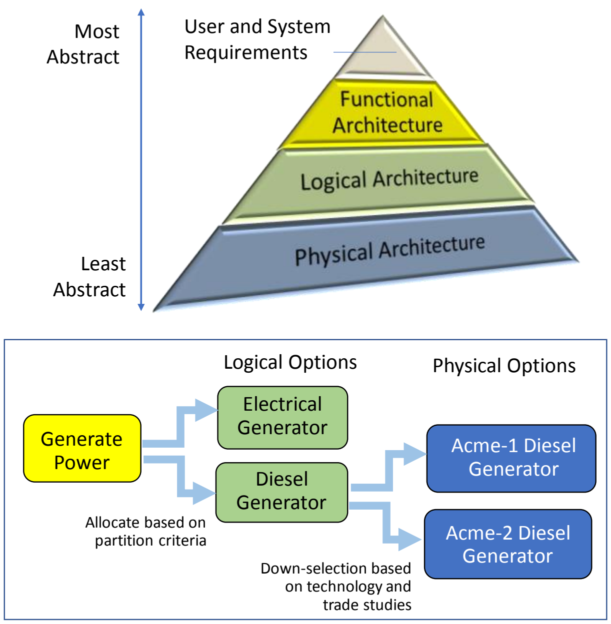

Fig. 6. Architectural levels, employed in the modelling of the DEMO Breeder Blanket.

builds upon the systems operational concept. It comprises a set of functions and their sub-functions and interfaces (internal and external) that defines the transformations of input flows into output flows required to achieve the operational goals.

The benefits of developing a set of derived functions in this way (and associated flows of energy, materials and information) include the following:

- Provide a description of what the system must do in as generic a way as possible.
- Identify functional options – different ways of achieving the same goal from an operational point of view (and subsequent selection of the most appropriate option).
- Informs internal and external interface studies.
- Derived functions are allocated to system elements of the Breeder Blanket.

This early work has focused on the system behavior during a plasma pulse.

C. *Findings*

It took time for this new way of thinking (about the required behaviors of the system irrespective of underlying technologies) to be understood by domain experts.

In addition, the nature of blanket processes, and the degree of interconnectedness between them has taken time (and much iteration) to determine.

However, having gone through this process, what the team have found is that this approach provides a new way of thinking about and describing the problems space; the modelling approach has served as a good discussion/communication method (establishing a common language), offering a “unique perspective” in an area otherwise dominated by detailed engineering design and analysis studies.

Modelling of Functional Architecture has been undertaken using SysML Activity Diagrams, which are ideally suited to modelling energy and material flows between physical processes.

What the analysis tells us so far:

- Reconsideration of system boundaries following Systems Engineering principles: Analysis is ongoing, but areas under consideration include local Instrumentation and Control directly associated with Breeder Blanket processes, and the extraction of Tritium from the Breeding Blanket substrates (e.g. breeding/multiplying materials / fluids).
- Identification of functional variants: Analysis is ongoing, but as an example, functional variants are identified for breeder and multiplier nuclide supply schemes, which may be either batch or continuous in nature.
- The requirements specification can be revisited, and further requirements can be identified based on the work done so far.
- Links to analytical modelling: Provision of a clear framework for physicists developing software for coupled multi-physics codes is offered by the functional architecture. The system model provides a list of functions, arguments, return statements and hierarchy that could form part of a software specification for analytical modelling activities.

The success encountered with the methodology, language and software tools used during this development have informed Systems Engineering training activities within the DEMO community, where a similar approach for other work packages is encouraged. The SysML pilot has been deemed successful, in that SysML is now the language recommended for use on DEMO for the foreseeable future.

D. *Future Direction*

The overall goal is to develop an objective framework for assessing system design choices against the required functionality.

Discussions are taking place at the time of writing on how the foundations established this year on Breeding Blanket system (engineering) model can be further developed and integrated with Plant level architectural work.

Further developments on the BB model should include:

- The development of use cases and functions applicable across the DEMO Lifecycle. This should include examination of abnormal operating conditions.
- The development of a logical architecture for the Breeder Blanket. The functions derived from the functional architecture should be allocated to these logical systems.
- Options should be explored to establish an integration of Systems Engineering and analytical modelling workflows.

Further work should examine in detail key interactions and dependencies with neighboring systems, including Balance of Plant and the Fuel Injection System, together with further work on RM and Heating & Current Drive. This will inform the interface requirements and specifications.

The system modelling approach could draw in simulation results from other studies which are seeking to optimize the design. The construction of parametric CAD (with varying detail levels) and performance of simulations (engineering, physics, neutronics) on the geometry could be used to provide performance metrics for a range of configurations.

VI. Case Study 4: European Spallation Source Active Cells

A. Context Overview

The UKAEA were awarded the contract to deliver a radiation hot cell to facilitate the disposal of highly radioactive components from the European Spallation Source (ESS) based in Lund, Sweden. The hot cell is intended to be a remotely operated facility, used to size reduce the large components, place the parts in waste packages, interim store the packages and finally remove the waste to be transported to an external Swedish waste disposal facility.

The ESS Active Cells project is complex both in terms of its technical challenges but also from an organizational point of view.

Technical challenges include:

- A highly radioactive environment both in terms of gamma shine and radioactive particulates
- Inheriting a frozen design for the concrete structure
- No windows
- Remote maintenance
- Bespoke technical solutions such as remotely operated cutting devices
- Many interfaces

Project challenges include:

- A multidiscipline project team; spanning mechanical engineers, electrical engineers, software engineers, control system engineers, radiation physicists
- Multiple organizations; the UKAEA have taken the role of systems integrator, managing multiple organizations but also ensuring that the Active Cells system, which itself is part of a wider system, meets the needs of the customer
- Tight timescales; delivering a complex hot cell in only 4 years

The Active Cells project was started by the ESS organization and taken to a system concept stage where by UKAEA took over responsibility for the detailed design, manufacture, installation and commissioning of the equipment within the facility.

B. Application of Systems Engineering

Upon handover of the project from ESS to the UKAEA it became apparent there were two approaches that the UKAEA could take in developing the system; the first was to immediately begin carrying out the detailed design, evolving the inherited concept designs for individual pieces of equipment to the point that a number of individual products could be manufactured, but with no real appreciation for the overall system. This would be in the absence of detailed requirements which are integrated at a system level, potentially resulting in many manufactured elements of the system which do not necessarily integrate to achieve the customer's needs.

The second approach, a Systems Engineering approach, the approach eventually taken by the UKAEA, involved going back a step in the development process and creating a set of system requirements. These were generated from the user's or customers' requirements i.e. what does the system need to do to satisfy the customer's need? From here, the subsystems could be defined, resulting in further requirements but at a hierarchal level below that of the overall system. This process ensures that all requirements at the subsystem level are linked to the system requirements and all design decisions were documented fully, giving confidence that all integrated subsystems will combine to meet the overall system requirements. The process was repeated another hierarchal level below that of the subsystems, called the Equipment level. Equipment level requirements were the lowest configurable level of the system and the point from which the system's lifecycle progresses from requirements definition to engineering implementation, that is, design and manufacturing.

Following the manufacturing of all equipment level elements of the system, they will be integrated into their subsystems, which will also be integrated to form the overall system. Testing will be conducted following the manufacture of equipment, their integration into subsystems and the integration of the entire system. This will be used to ensure that compliance against requirements at all hierarchal levels is achieved, providing confidence that the fully delivered systems meets the original needs from the customer.

In addition to the management of requirements and the integration and testing of the system's elements, UKAEA have developed an Interface Management Plan to manage the complexity of the system's constituent subsystems equipment. The plan details a common approach to ensure that all system elements can be designed concurrently between multiple organizations and project teams.

C. Findings

The following benefits from applying a Systems Engineering approach to the Active Cells project have been identified:

- There is confidence that the individual manufactured elements of the system will integrate to meet the needs of the customer.
- Multiple elements of the system can be designed concurrently, saving time on the critical path, with confidence that all elements will integrate together.

Many lessons have been learned in implementing Systems Engineering on this project, the key lessons learnt include:

- Any process which is to be followed, be it a requirements management process, verification management process, interface management process must be clearly and unambiguously defined as early into the project as possible. This ensures that all outputs are created in a uniform manner and prevents rework by retrofitting an output to a later defined process.
- Whilst creating formalized processes is important, it does not, by itself, mean that Systems Engineering will be a success. It is important to also ensure that there are enough Systems Engineers on the project to help in applying the processes, assisting those who are perhaps not

experienced in SE practices.

- It is much easier to apply Systems Engineering to a project when the impetus to do so comes from the top of the organization and is filtered down. This will ensure that:
  - o There is a drive to provide upfront budget for SE resource.
  - o There are adequate organizational procedures in place.
  - o There is an adequate SE presence on the Design Authority panel.
- It will not always be possible to apply the fully intended Systems Engineering process during the entirety of the project, especially for long lead time items. Where the process has not been adhered to, the risk associated with this should be recorded accordingly.
- It is always tempting to spend the minimum amount of time on requirements and get stuck into a design on the basis that, 'we know what we need to do, let's just get on and do it'. This is a risky approach to take and may lead to the delivery of a system that does not meet the stakeholders needs. It is important to spend time in fully defining the requirements along with the verification activities needed to show full compliance.

D. Future Direction

The UKAEA's contribution to the ESS Active Cells project is moving from the requirements phase and into design, manufacturing, integration and commissioning phases. To ensure that the as realized system complies with the system requirements and ultimately meets the customer's needs, verification of requirements is key. In the coming months, we will specify tests to provide progressive levels of assurance as the lifecycle progresses and eventually final acceptance. These tests will be compiled into detailed verification plans which will be used to ensure that all verification activities are carried out and fully documented.

It is anticipated that the groundwork laid in ensuring that requirements and interfaces are clear at the design stage will ensure that the path to commissioning will run swiftly and smoothly.

VII. COMMON LESSONS LEARNT

There are a number of common threads which can be drawn together from the experience gained at UKAEA in applying Systems Engineering. The primary benefits observed so far can be summarized as follows:

- The application of a rigorous requirements capture process from the top-level down has brought clarity, helping us to understand the fundamental needs that the systems we are designing must satisfy.
- Creating System Architecture models have provided a fresh functional perspective that has enabled us to challenge existing preconceptions and assumptions.
- The use of the SysML modelling language and tools such as DOORS have provided a clear common format and language for communication. This has facilitated coherent and consistent understanding.
- This foundation of requirements and architecture allows us to rigorously assess design options against the correct criteria to ensure that optimal design choices are selected.

VIII. CONCLUSION

The experience of applying Systems Engineering at UKAEA has demonstrated that systems thinking coupled with a requirements led design process is beneficial. However, the case studies in this paper only cover the first half of the project lifecycle. The full benefits of Systems Engineering which are well known in other industries [23], will only be fully seen when the project has been completed. It is at that stage, that the value of the extra effort to characterize the desired system in the early stages can be demonstrated in the delivered system.

The authors of this paper conclude that the short-term benefits already observed, along with the longer term anticipated benefits, justify the wider adoption of Systems Engineering within civil Nuclear Fusion.

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