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Benefits of using model-based systems engineering at Wendelstein 7-X

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Abstract

The paper presents the concrete benefits of applying a model-based systems engineering approach using selected examples in the life cycle of Wendelstein 7-X.

I. INTRODUCTION

Systems are according to ISO/IEC/IEEE 15288 *man-made, created and utilized to provide products and/or services in defined environments for the benefit of users and other stakeholders* [1]. Experience has shown that the requirements placed on technical systems increase steadily with the progress of technical development. In order to perform the desired, increasingly sophisticated functions, mechanical subsystems must be combined with electrical/electronic and, more and more frequently, digital based information processing subsystems to form an overall mechatronic system. The result is an intricate as well as complex system. Intricacy refers to the number of different elements in a system, complexity to the number and type of relationships between these elements [2]. Characteristic of such complex systems are emergent properties, i.e. properties that are unique to the overall system and not to its associated subsystems. In order to implement all the positive, desirable system properties, but also to identify and eliminate possible negative, undesirable properties at an early stage, the systems have to be analyzed in an appropriate way.
Capturing the complexity of existing systems, representing the interdependencies and interfaces between elements, and designing systems according to stakeholder requirements is one of the objectives of systems engineering (SE). SE is interdisciplinary and attempts to take a holistic view of systems. The performance of a project or program has been shown to increase with the use of SE [3]. According to SE principles, every system has a life cycle. Every system is by definition composed of a set of interacting system elements.

Systems engineering methods are by now also being applied in fusion research [4, 5, 6]. Looking at the fusion experimental facility Wendelstein 7-X (W7-X) with its superconducting coil system, plasma heating systems of different effective methods and a multitude of plasma diagnostics, it is probably indisputable that it meets the definition of a complex technical system. Accordingly, the application of SE should develop tangible benefits here as well.
The mission of W7-X is to demonstrate the reactor suitability of the HELIAS concept (HELical Advanced Stellarator) [7]. W7-X has successfully completed three phases of operation by now. Currently, the device is in preparation for steady-state operation [8].

Activities in the course of SE should be oriented to the ISO/IEC/IEEE 15288 mentioned above.This defines 25 key processes which, in their entirety, span the entire life cycle of a system and should be run through during the development of technical systems. Each process is divided into individual activities, requires an input and generates an output. Although the process activities are specified in the standard, the scope and the methodology to be used are the responsibility of the systems engineer. In addition to the document-centric methodology, which has always been the norm, the W7-X project also follows a model-based approach, the model-based systems engineering (MBSE). According to INCOSE 2007 MBSE means *the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases* [9]. In this paper, we focus more on the latter two phases.

II. BASICS OF MODEL-BASED SYSTEMS ENGINEERING

During the system analysis by means of MBSE, the existing or still to be developed technical system is decomposed step by step into its individual elements. Finally, all system information are captured in a model instead of or at least in addition to what is written in documents.
In the project we are using the formal graphical language SysML for modeling which is based on the Unified Modeling Language primarily used in software project. Thus, the model is available in a graphical form. Basic design elements are, quite simple, blocks which are connected by edges. Depending on the diagram type these elements have different meanings. SysML offers a total of nine diagram types to model system characteristics, e. g. block definition diagram to model how system elements are defined and what relationships exist. System characteristics can be structural or behavioral. The diagrams that arise in this way enables various views of the system. Each type of diagram addresses only an isolated aspect of the system, but only with all diagrams

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together, you can describe a system fully. System engineers call the totality of all diagrams the system model. Advantages of using formal languages such as SysML are that the modeled aspects are computer interpretable and executable if appropriate software is used, as well as changes to a model are proliferated through the design compared to continually manually updating all documents.

III. THE W7-X SYSTEM MODEL

The system model is initially only the generic term for all modeled aspects. The concrete composition of the system model depends on the objective of the modeling. Thus, the system models can pursue various purposes. For example, it can help to characterize an existing system or to make fundamental architectural decisions in the concept phase [10].

The project first modeled the system objectives, which can be derived from the mission (system idea) of W7-X. This modeling forms a kind of "hierarchical superstructure" that serves as a superordinate reference. All other modeled aspects and those to be modeled in the future can refer to this and thus be placed in the overall context.

In this paper, the superstructure is presented only to the extent necessary for understanding the modeling examples. For modeling the superstructure, the SYSMOD approach was used in the project. All diagrams were created within the Cameo Systems Modeler^{TM} Environment.

According to Weilkiens, SYSMOD is a *MBSE toolbox for pragmatic modeling of systems and offers a set of methods with roles, inputs, and outputs, concrete modeling guidelines* [11]. The method concretizes the technically abstract development process [1] and offers a kind of "recipe" in the form of a structured top-down analysis for the project developers. The general aim is to build a system that meets stakeholders needs.

According to SYSMOD, the following steps have to be performed roughly one after the other:

1. Define system idea, objectives and stakeholder
2. Identify requirements
3. Model base architecture
4. Model system context
5. Define system use cases
6. Model logical architecture
7. Model physical architecture

Here, steps 1 to 5 can be interpreted hierarchically as the top-level of the system, to which all further deeper analysis steps can be referenced. The logical view contains all technical concepts and principals that have been chosen to fulfill the top-level requirements. This can be an extensive modeling step. However, on the logical level there is nothing said about which element takes over the defined tasks and – more fundamentally – which physical elements the system shall or actually consists of. Therefore, the physical architecture should also be modeled. The logical elements can then be mapped to the physical and vice versa.

In the case of an already existing system, this basically means that the information that usually held in artifacts such as documents are translated into SysML notation and are related in a model, taking into account different points of view. This sounds banal at first, but the application leads to the essential properties and reveals possible hidden dependencies, which are not immediately obvious. This shall be illustrated by the example of the system use case analysis for the technical operator (Figure 1).

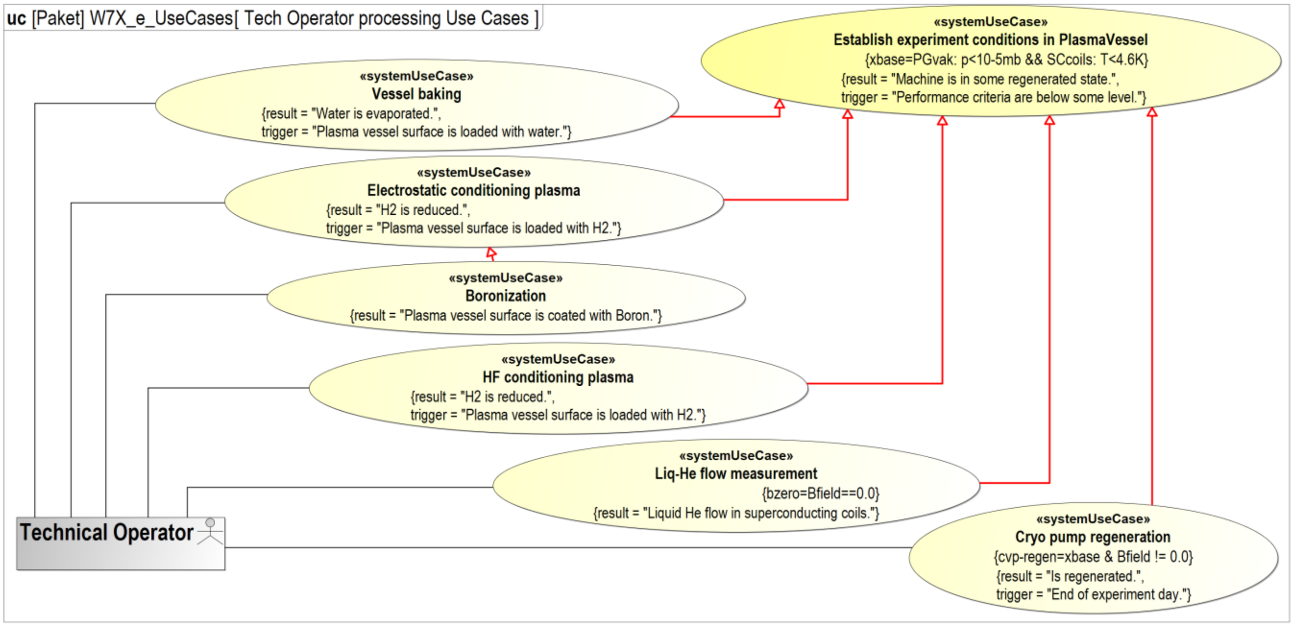

Figure 1. Refined functional requirements as system use cases related to technical operator (a selection is shown)

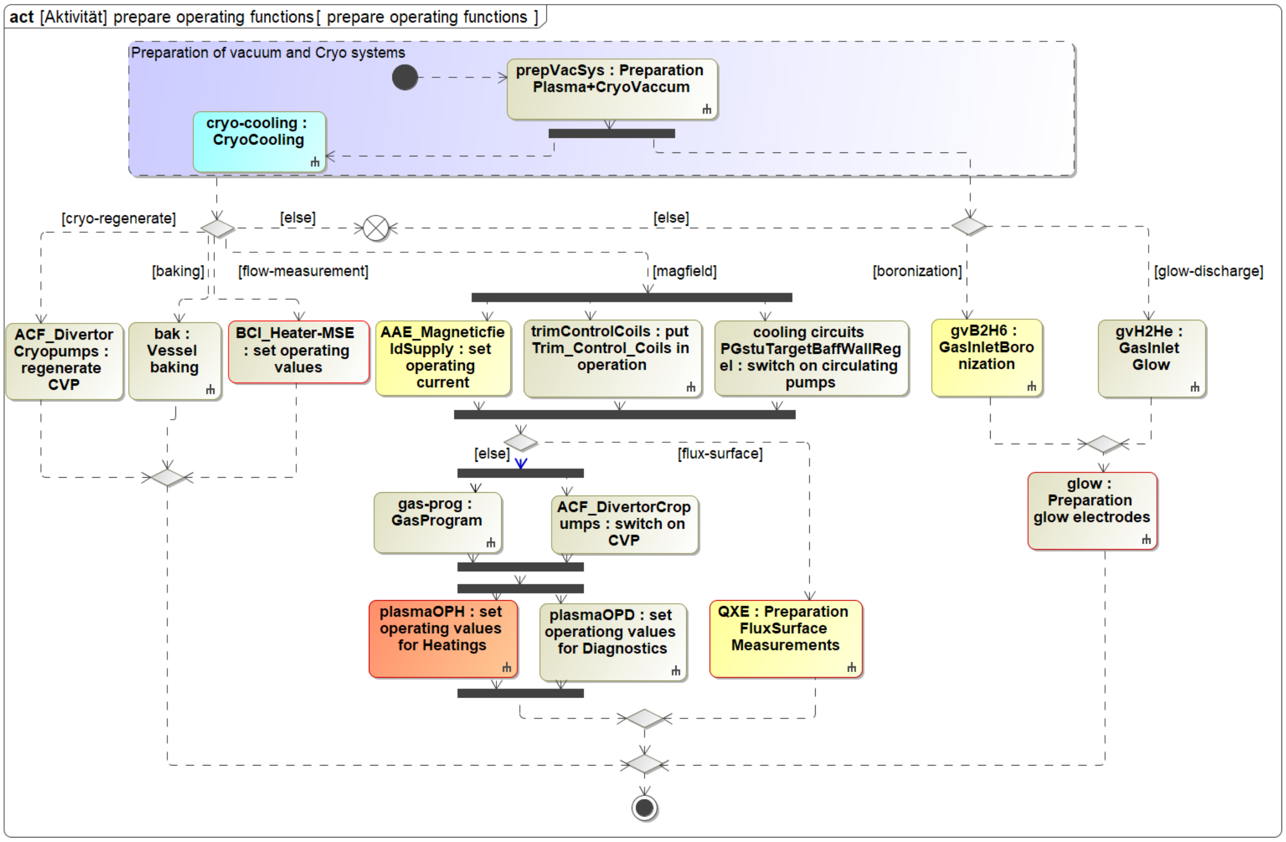

Figure 2. Activity diagram of execution order of system use cases.

The system use cases can generally be derived from the functional requirements. An important functional requirement is the preparation of plasma vessel (PV) for experimental operation. At the systems level, this results in the use case of *establishing experiment conditions in plasma vessel*. To reach this some other use cases are necessary like *vessel baking*, *electrostatic conditioning* (glowing) or *boronization*, which are in responsibility of the *technical operator*. The individual use cases are not isolated, rather there are interdependencies between them. When you bring the use cases into the logically executable order as in figure 2, taking account the interdependencies, you get a first structure of a system process order (operation possibilities). For example, *vessel baking* and *glowing* are only possible with evacuated vessels, but *baking* also requires the circulation of cooling circuits.

The system analysis thus supports activities that are strongly coordinated, such as the planning of commissioning and the actual experimental operation phases (see example 2 as well).
The benefits of using MBSE will be illustrated in the following by two further modeled aspects.

IV. EXAMPLE 1 – INTEGRATE NEW COMPONENTS

MBSE also supports the operational integration of new components into the existing device, as illustrated below with the integration of the cryopump system.

A. *Cryopump states*

For the coming operation phase (OP) 2.1 we are integrating a system of ten cryopumps in order to allow efficient control of plasma density and for screening impurities [12]. Three different cooling media flow through each cryogenic pump simultaneously: Water, nitrogen and helium. Each medium has its own circuit. There are dependencies between the operation of the individual circuits which must be taken into account when operating the entire system. For example, water circulation is a prerequisite for the operation of both the nitrogen and helium circuits. The dependencies were modeled by a state machine (Figure 3). The state machine can be executed so that each constellation can be played through, revealing the dependencies. The three different circuits are arranged vertically in the figure. In this case, each block within the diagram represents a specific operating state and each edge stands for a state change, which can be linked to specific conditions, such as the state of the other two circuits.

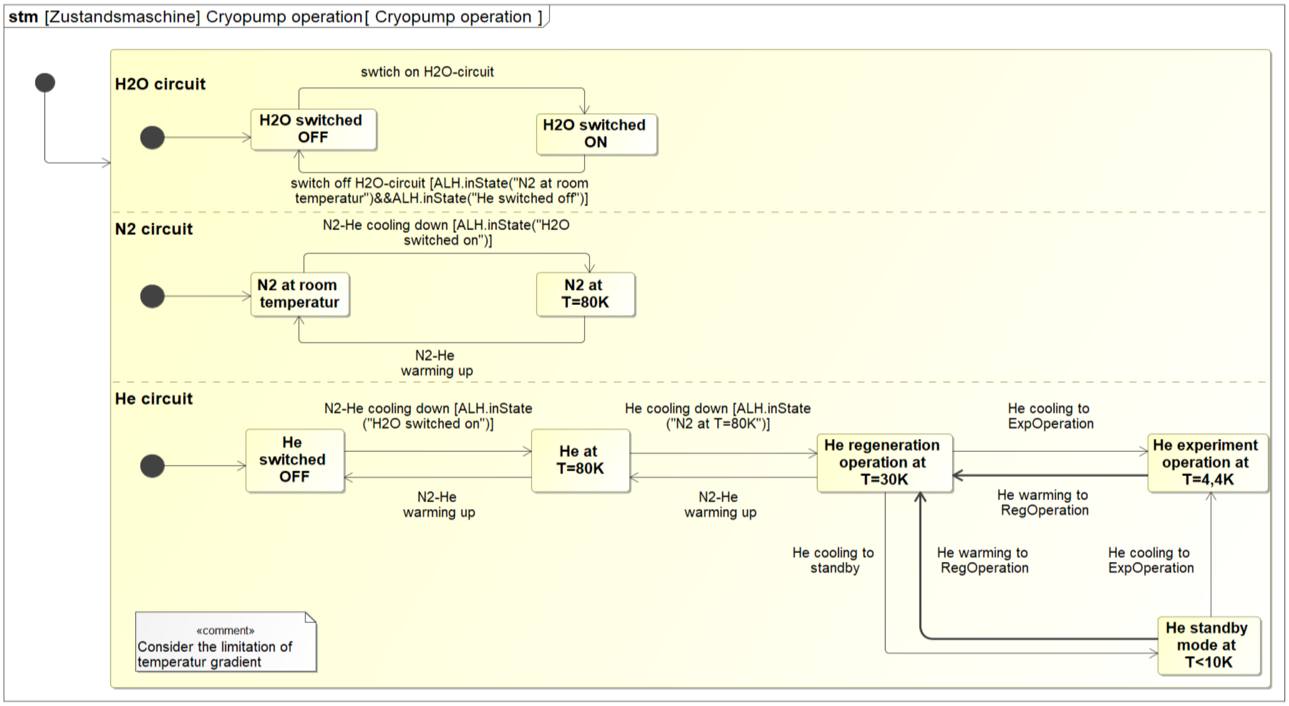

Figure 3 The state machine of the three different cooling circuits of a cryopump in W7-X

B. *Cryopump operational activities*

With the help of the state machine, it was possible to define the needed execution order for cryopump operation (Figure 4), which includes regeneration phases (notice the corresponding system use case in figure 1). During plasma operation, the unwanted substances are bound to the cold surfaces of the cryogenic pumps, so that their pumping capacity decreases with increasing load. This makes it necessary to regenerate the cryopumps from time to time by heating the cold surfaces. In preparation for operation, the regeneration intervals have to be specified and the sequence has to be coordinated.

It is foreseen, that the regeneration is split into two phases. After each experimental day, there is a daily regeneration from 4 K to 30 K to remove any adhering hydrogen, and after the entire week of experiments, there is a weekly regeneration to room temperature to remove any other adhering material.

The regeneration itself consist of the actual warmup (activity diagram not shown). Important information like that the warmup is expected to take 30 minutes can directly be highlighted as a comment in the diagrams.

(Notice: For each activity in the activity diagram, sub-activities are modeled when a trident icon is displayed in the bottom right corner of an activity block.)

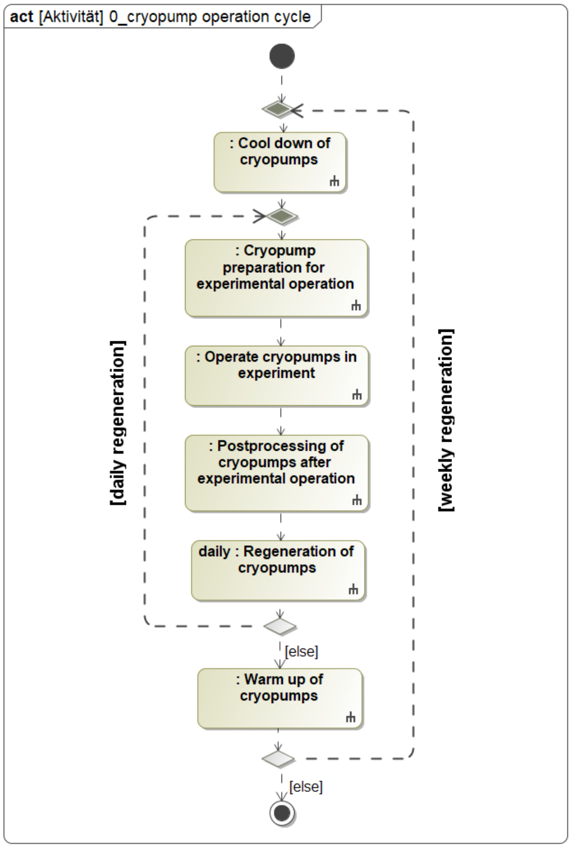

Figure 4 Key activities of operation cycle of cryopumps in W7-X modeled by activity diagram; trident icons indicate more activities with more details modeled

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After the substances released back into the plasma vessel by the heating of the cold surfaces, they must be pumped out of the vessel. When switching on the pumps, it must be considered that the root as well as the turbomolecular pumps expect a certain pressure level to avoid failure mode. So depending on the actual pressure in the vessel, the pumping system must be operated in the correct stage (Figure 5).

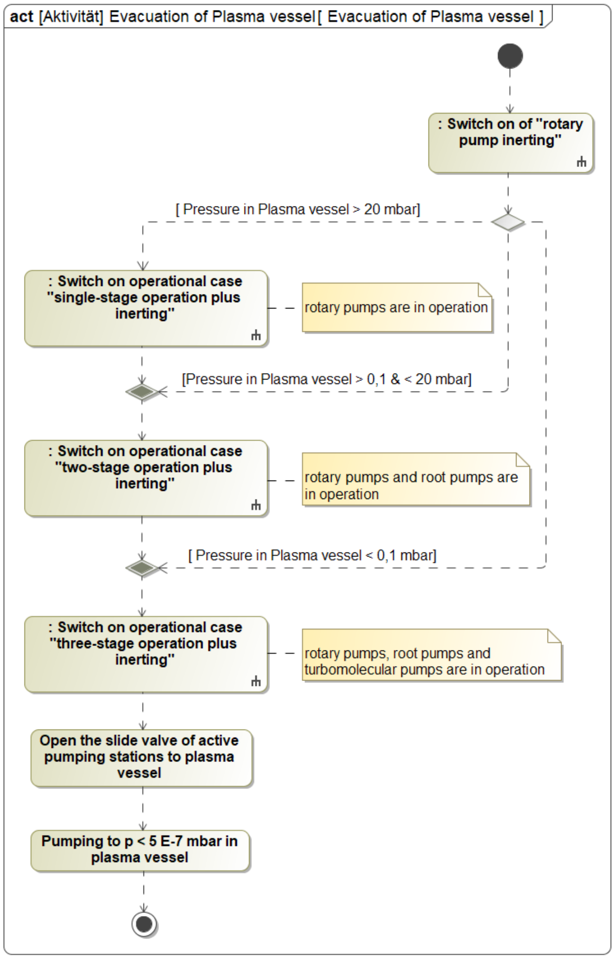

Figure 5 The process of re-evacuation of plasma vessel with regeneration after cryopump warmup

In summary, the set of diagrams were a great help in coordinating and defining the forthcoming cryopump operation. At this point, MBSE thus served distinctly to build consensus among team members.

V. EXAMPLE 2 – UPDATE CENTRAL SYSTEMS

In the following, the benefits of MBSE in updating the central safety system (cSS) of W7-X are illustrated.

For safe operation, W7-X has various central control systems [13]. The cSS as the safety instrumented system (SIS) is designed according to the international safety standard IEC 61511 [14]. In order to avert danger to persons and the facility, the SIS performs actions. Which actuators must intervene in a defined manner for which states of sensors is specified in the safety requirements. At the end of the development process, before any hazards are actually generated, each sensor-logic-actuator safety chain must be validated in a site acceptance test. For OP2.1, the cSS was profoundly updated. Fifty different integrated safety functions containing a vast number of sensor-actuator relations were defined. The challenge is to perform the validation of the entire functionality of the SIS in an efficient way that takes into account the specifics of the components and the overall device in the commissioning phase. This is where MBSE came into play again.

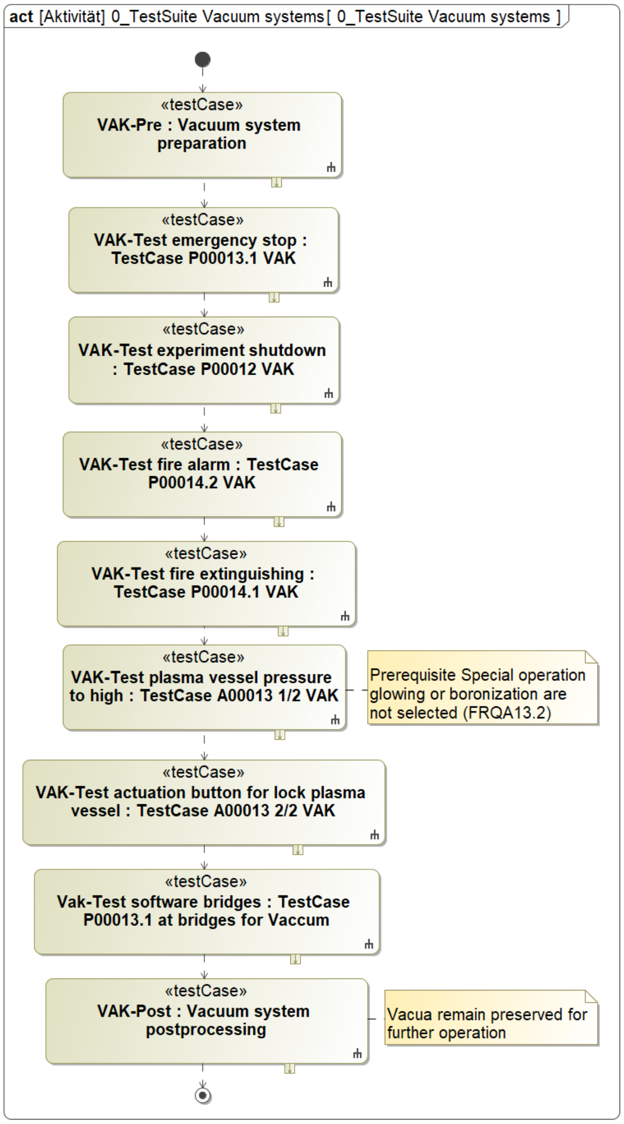

Figure 6 Activity diagram of component-related test suite for validation of vaccum pumping systems for plasma vessel, cryostat and the intermediate space between both components

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C. Step 1 – Check operating dependencies

For planning of validation, the question arises, which functionality can be tested in which operating state and at what device accessibility. First, all dependencies of the defined operating functions (similar to figure 2) were modeled. Some operating functions are linked to preconditions, resulting in restrictions in the choice of operating mode. Some states are mutually exclusive. For example, it is not possible to glow when the magnetic field is up. Thus, that the safety function is acting in each state cannot be tested within one test case. With MBSE the validation could be divided and structured. For example, it makes sense to split the validation into one continuous block when the access to the facility is open and one block when it is closed, in order to minimize the impact on the parallel completion work that requires access. The modeling also resulted in a schedule of which components must be ready for use on which date.

D. Step 2 – Generation of requirement-based test cases

The generation of the validation test protocols was done with the help of MBSE. First, all sensor-actuator relationships were transferred to the model as requirements and corresponding test cases were created. The test cases are combined into test suites according to the above criteria, which is shown in Figure 6 using the example of the common test plan for the vacuum pump systems of the vessels. Each test plan includes a pre- and post-processing. Each test case can be assigned a test verdict after it has been run. A test case, in turn, is composed of the essential test steps – the actions to be performed during the test (Figure 7). By whom the actions have to be executed can be graphically represented additionally via vertical "swim lanes", whereby the actors (component operators) are allocated to the test steps.

By using the formal language SysML the models are in principle executable. The sequence compiled by activity diagram can thus be exported and corresponds to the test protocol, which has to be run by the tester during the validation step by step.

To check the completeness of the test plan coverage, i.e. that each safety requirement is met by a test case, commercial MBSE software usually offers the convenient representation by verification matrix.

Advantageous is the preserved flexibility in protocol generation. All test cases are stored in a library and can be rearranged without having to make changes to the content. Future modifications of the SIS can also be easily incorporated into the validation planning via new test cases.

VI. BENEFITS

General, rather project-unspecific advantages resulting from the use of model-based systems engineering are:
- Structured documentation of design decisions.
- The traceability of design decisions to requirements
- Consensus building among stakeholders, avoiding misinterpretation of system structure or behavior during internal and external communication
- Clear representation of complex interdependencies between system elements.
- Support holistic considerations such as system safety and operational concerns.

Specific advantages reflected in the examples shown:
- Enables optimization of operational processes
- Enables planned "smooth" integration of components
- Enables central systems to be updated as requirements change or new requirements are added.

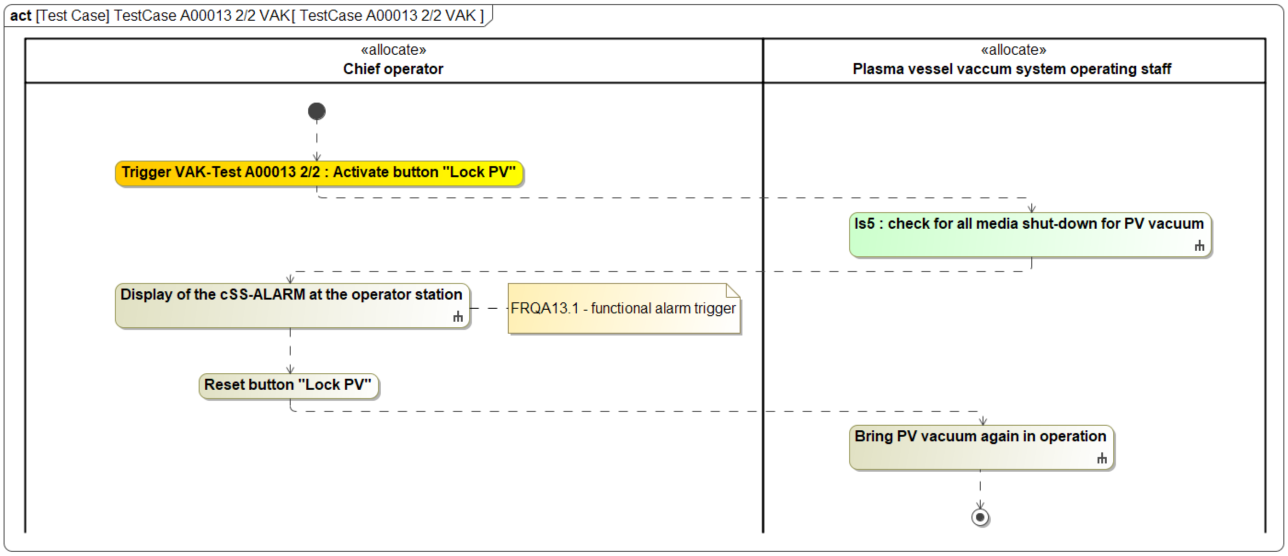

Figure 7 Activity diagram of test steps in test case for lock plasma vessel after activation of "Lock PV"-button

VII. NEXT STEPS

The examples illustrate the benefits of using MBSE. The decision to continue using MBSE was therefore not difficult. The next steps will be the completion of the superstructure and the logical as well as the physical structure for the subsystems. The top-down approach will be continued (1. identify element, 2. describe context, 3. dive into details). The level of modeling depth will be guided by the goal of complete modeling of normal and degraded operations.

VIII. SUMMARY

Model-based systems engineering is a powerful tool for managing the complexity of technical systems. As shown in the article, the application possibilities are not only limited to the early concept phase, a significant benefit can also be achieved in later system life phases such as commissioning and machine operation. It is planned to continue using MBSE in the W7-X project.

IX. ACKNOWLEDGMENTS

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