PRODUCT DEVELOPMENT SUPPORT FOR COMPLEX MECHATRONIC SYSTEM ENGINEERING– CASE FUSION REACTOR MAINTENANCE

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ABSTRACT

Development of a multidisciplinary mechatronic system, like a remote operated maintenance system of ITER fusion reactor, requires system engineering approach. System engineering is a leadership approach for designing totally new concepts and technology. On the other hand, system engineering needs support for managing all related processes and information. Product lifecycle management (PLM) can be seen as IT-aided enabler of such processes and information management desires. Divertor Test Platform 2 (DTP2) is a full scale mock-up and test facility for developing, testing and demonstrating remote operated maintenance equipment as well as planning and training future maintenance operations. Characteristic for DTP2 is that its development and operational lifecycle will be several decades long. History of the system has to be traceable and all data must be available during the whole lifecycle. This work in progress paper aims to introduce the first results of the ongoing project, which defines and implements PLM support for DTP2 system engineering. The preliminary results include requirements specification for the PLM platforms, and a concept for mechatronic product model and data model.

Keywords: System engineering, mechatronic system, design support, PLM

INTRODUCTION

ITER is a large-scale scientific experiment intended to prove the viability of fusion as an energy source, and to collect the data necessary for the design and subsequent operation of the first electricity-producing fusion power plant [1]. DTP2 (Divertor Test Platform 2) facility (Figure 1) is supporting the ITER project. *DTP2 is a full scale physical test facility* intended for testing, demonstrating and refining the remote handling (RH) equipment designs with prototypes. The facility will also be used for training future ITER RH operators. Effective and efficient remote replacement of the ITER divertor is central to the successful execution of the ITER project. The aim of the DTP2 is to ensure that the cassette movers supplied to ITER during its construction are based on well-matured designs which have benefited from the experience from the building and operation of a first generation of prototypes. [2], [3]

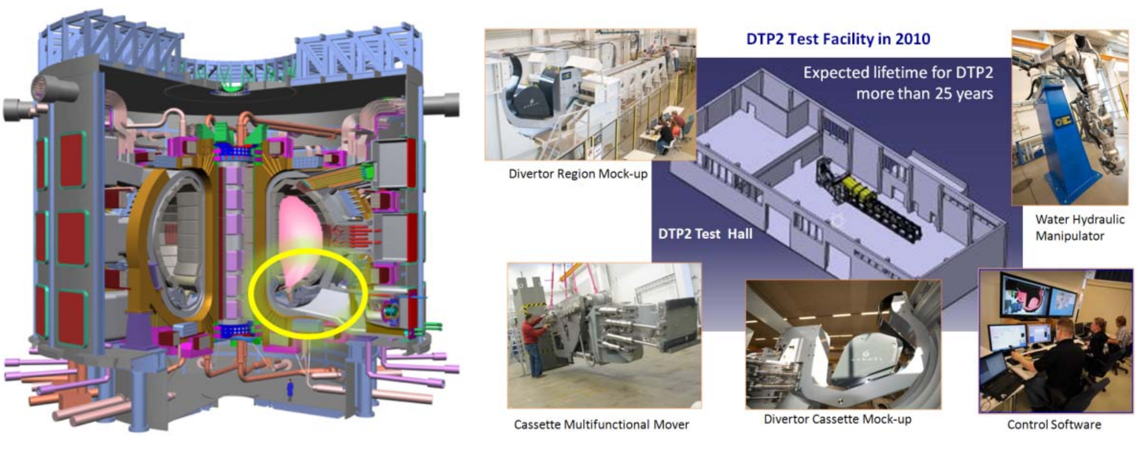

Figure 1. ITER fusion reactor and the DTP2 mock-up facility

System Engineering and Product Lifecycle Management Approach

System engineering is an interdisciplinary approach for designing totally new concepts and technology. There exist many definitions of the system engineering. According to Kossiakoff [4] the characteristics of a system whose development require the practice of system engineering are that the system: is a engineered product which satisfies a specified need, consists of varied components that have complicated relationships, is multi-disciplinary and relatively complex, uses advanced technology, involves development risk and relatively high cost, it's development requires several years, many interrelated tasks and several organizations to complete. The role of system engineering is to seek the best balance of the critical system attributes and engineering disciplines. All of these characteristics do not exist always, but in case of fusion reactor and divertor development they are very relevant. The system engineering method can be thought of as the systematic application of the scientific method to the engineering of a complex system, though it does not correspond to the traditional academic engineering disciplines [4].

A system (or product) lifecycle means evolution stages from requirements through concept development, design, production, operation and maintenance to disposal. In system engineering these stages can be referred as 1) concept development, which is the first stage of system concept and functional definition in order to satisfy a specified need, 2) engineering development, which translates the system concept and functions into validated physical system design, and 3) post-development including production, deployment, operation and support throughout the system life. The post-development is also very important stage, since system engineering is often needed for instance in problem solving during the operation and maintenance of the system. This is likely one way to utilize DTP2 facility in the future. Therefore, traceability of the system development and documentation is essential.

System engineering is integral part of a system development project as well. A large project involves often hundreds of people and several organizations. One of the most important functions of system engineering is to guarantee communication between disciplines and parties through documentation and other communications. Besides conventional text and drawing engineering documents, these include nowadays also e.g. simulation models and videos. These documents are revised periodically. Therefore, it is essential that documents and other information are well managed. System engineering method (Figure 2) can be considered as consisting of four basic activities: 1) Requirements analysis (problem definition), 2) Functional definition (functional analysis and allocation), 3) Physical definition (synthesis, physical analysis, and allocation), 4) Design validation (verification, evaluation) [4].

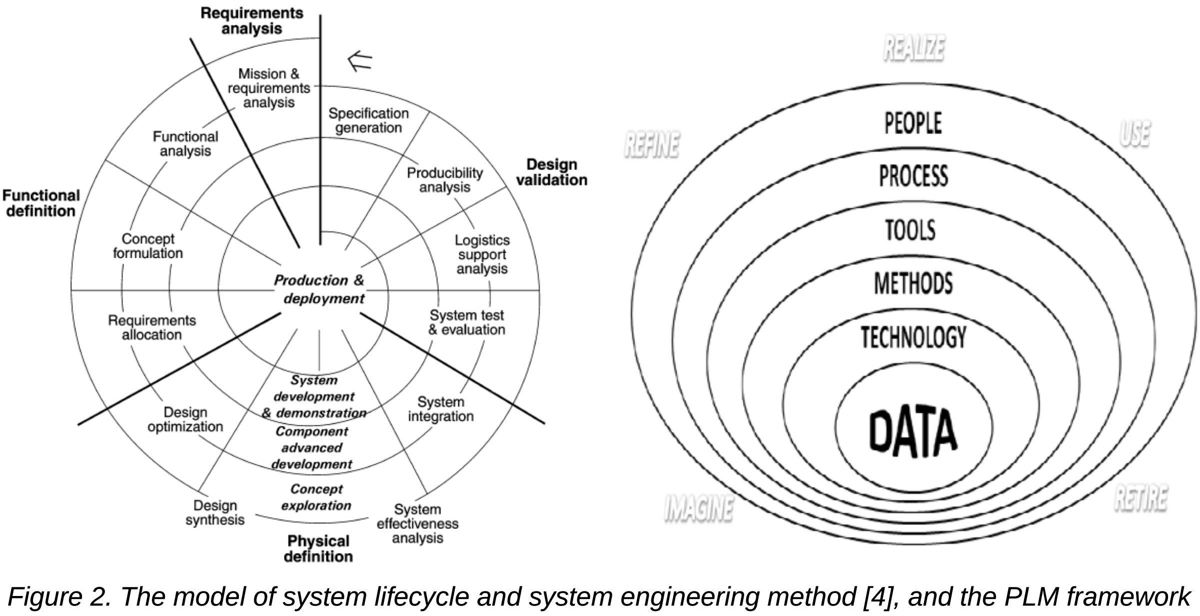

Figure 2. The model of system lifecycle and system engineering method [4], and the PLM framework

Development of a system including totally new concepts and technology faces often unknowns regarding performance of the implemented system. Experiments and simulation are powerful means for verification and evaluation of system performance, as well as for decision making and problem solving throughout the system lifecycle. Simulations and experiments can be utilized both for system functional and material behavior assessment, and they offer complementary information [4].

Product lifecycle management (PLM) is an integrated, holistic information-driven business approach comprised of people, processes/practices, and technology to all aspects of product's life, from its design through manufacture, deployment and maintenance. Components of PLM include the products themselves, organizational structure, working methods, processes, people, information systems and product data. [5],[6]

The right side of Figure 2 illustrates the components of product lifecycle management. Product definition data is the core of PLM. It includes specification of the product itself, but also production, maintenance, disposal and all other specifications during its lifecycle. The data is nowadays often in digital format, but it includes physical documentation as well. PLM technology includes data management and other systems, like PDM (Product Data Management) and ERP (Enterprise Resource Planning). PLM tools and methods include systems and procedures for producing, analyzing and utilizing product data, e.g. CAD (Computer Aided Design), VR (Virtual Reality), AR (Augmented Reality), DFX (design for lifecycle) and CAE (Computer Aided Engineering). There are many kind of processes involved during product lifecycle, from concept design to detailed design, production planning, usage and maintenance. People involved in product lifecycle management are organized in a complex network including different internal departments of a manufacturing company and external partners and suppliers. In present implementations, PLM is usually utilized in detail engineering and design phase, not in the fuzzy concept or research phases.

System engineering and PLM approaches have lot of similarities. System engineering is strong in multidisciplinary engineering and systematic chain from end-user requirements to functional and systematic breakdowns and finally to physical breakdowns, technical solutions and system validations. PLM should support these activities for instance with good requirements and engineering change management capabilities. It is currently a popular research topic how to better implement System engineering in PLM. System engineering is quite an old theoretical approach which seems to have now revival because of development of PLM capabilities. Simulations and virtual prototyping of mechatronic systems are enablers of System engineering as well. On the other hand, PLM is strong both in product type and product individual data management. Those capabilities could be better utilized in System engineering. There are also design theories and many applicable product development methods defined for instance by Andreasen & Hein [7] and Ulrich & Eppinger [8]. Their strengths can be exploited in development and engineering of a mechatronic product. Those product development methods should be also supported by PLM [9]. We see System engineering and design methodology as complementary approaches. System engineering is more like a higher level framework for managing development projects flows from requirements to verifications and validations of a mechatronic multidisciplinary system, when design methodology supports delivering more detailed technical solution alternatives. Obviously there is overlapping between System engineering, design methodology and product lifecycle management.

Motivation and Objective

DTP2 is a complex high-tech mechatronic system consisting of many engineering disciplines and domains like mechanics, electronics, hydraulics, software development, virtual prototyping and virtual reality, and special new technologies like mobile robotics, water hydraulics, remote operation, and machine vision. In current phase of the project, management of the fuzzy front end of product development, including research activities, concept design, simulations, and virtual prototyping, is challenging. Technical and functional requirements for the DTP2 are high, since water-hydraulics driven remote operated system has to be capable for moving 9 ton divertor cassette with few millimeter accuracy and compensate mechanical and hydraulic flexibilities. Virtual engineering (VR, simulations, etc.) are utilized in several lifecycle stages: concept development, engineering design, remote operation, problem solving, visualization, etc. Virtual simulation models versions and revisions must be managed well. Projects around DTP2 involve a large network of organizations from universities to research institutions and companies. This kind of novel system development needs *system engineering approach*.

PLM is a framework to gain benefits in this kind of system development environment. With PLM it can be secured that right product information (version, status, change data etc.) is available at right time for different stakeholders during development, engineering, manufacturing, in-test and in-use. DTP2 has a very long life-cycle of several decades. From PLM perspective DTP2 is an environment which requires full product lifecycle support, from early development concepts until the in-test, and finally in-use period of the fusion reactor itself. PLM has to support the unique long in-test and in-use timeline of approximately 50 years. Besides the “traditional” PLM aspects (e.g. design configuration and individual configuration) of managing the definitions of product types and individuals, there is an important requirement to manage the information required for planning of execution of the divertor itself (e.g. maintenance programs and maintenance execution). Different product structure configurations and components, as well as simulations and test operations must be traceable during the whole life-cycle of the system. DTP2 will also be utilized in testing, risk analyses, problem solving, and training during ITER commissioning and operation. This means that even if the used IT –solutions of PLM most likely will change, the product data itself should be accessible for several decades. History of developing concepts and specifications of DTP2, and testing the DTP2 individual system must be traceable later during the whole life-cycle of the system, since cumulated information will be utilized in the actual ITER reactor construction, operation, maintenance, and problem solving. This requirement is in high importance level simply because of the fact that when the final fusion reactor operates no human can access directly the platform. There are extremely high safety critical requirements to fulfill. Systematic and accurate requirement management and change management processes are essential. Presently there is lack of IT-support for PLM of DTP2 development. From PLM approach point of view, there are also challenges in implementation because conventional PLM installations do not support system engineering of a mechatronic system in best possible way [10].

Because of increasing involvement of software development in a mechatronic system, the role of Software Configuration Management (SCM) systems have become important. Due to the lack of functionalities in the PLM systems, they cannot support the software development process. The software lifecycle including the development process is usually supported by the Software Configuration Management systems [11].

Virtual engineering, i.e. digital mock-ups and virtual prototyping, have been extensively used in DTP2. The digital mock-ups are used for planning and verifying task procedures of future remote handling test trials. During DTP2 operations, digital mock-ups will still be employed for improving, and validating test procedures. The final goal is to produce a complete digital mock-up of the divertor region and its RH equipment. There exist also challenges in virtual engineering of DTP2. The amount of virtual engineering related data is relatively large and increasing continually. Because DTP2 facility is subject to revisions, updates and upgrades, engineering changes together with virtual models’ versions and revision should be managed well. Data and specifications originate from different locations, therefore synchronization and reconciliation of data between parties is essential. These challenges need to be tackled with PLM features in future [3].

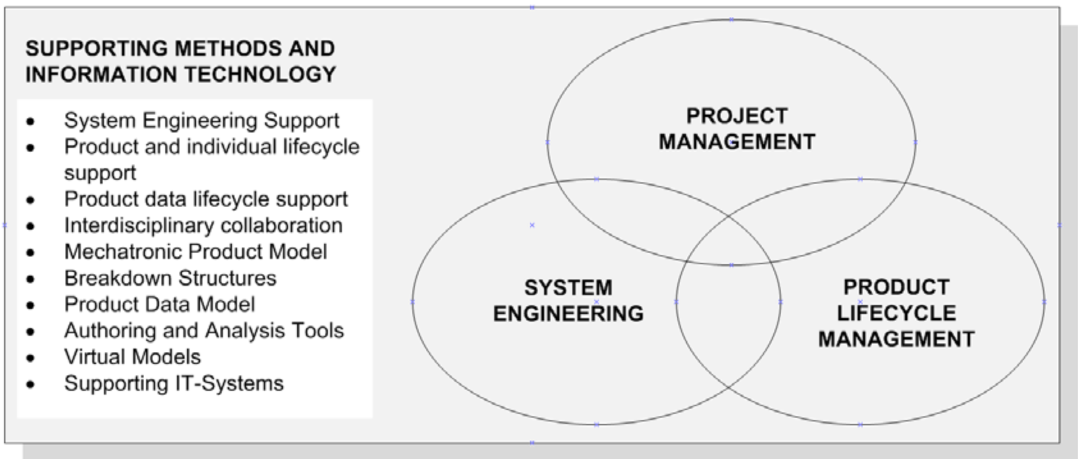

Figure 3. The concept of supporting system engineering approach and project management with PLM

Objective of the paper is to introduce a concept and the first preliminary implementation results of applying system engineering approach to DTP2 system development case supported by PLM and novel virtual engineering tools (Figure 3). The focus of the paper is in needs and requirements and conceptual solutions for the PLM.

METHODS AND MATERIAL

ITER related rules and procedures

As examples, two concept design tasks of the DTP2 are presented in this chapter. These are: 1) concept design of the Cassette Toroidal Mover, and 2) concept design of additional end-effectors for Cassette Multifunctional Mover (CMM). Concept design work that is done at DTP2 shall follow ITER rules. Design tool for mechanical design is Catia V5. Modelling work is done according to ITER CAD-manual. CAD-manual includes modelling rules and naming rules for 3D-models. Some attributes for 3D-models need to be added also because ITER will store all CAD information under their PLM system. First phase in the concept design process (Figure 3) is the gathering of the design input data. Design input data includes requirements for the design task. Source for these requirements is ITER System requirement documents (SRD). Typically SRD describes system basic configuration and boundaries, design, safety and quality requirements. Applicable codes and standards are also presented in the SRD.

After the collection phase requirements need to be analysed to evaluate their maturity and completeness. Priority of the requirements is defined and classified. Next phase in the system design approach is system concept definition. In the CTM concept design process this mean that CTM was divided to subsystems and comparison of the alternatives was done. For example the divertor cassette lifting devices electrical and hydraulic actuators options were compared. When the CTM was divided in subsystems, mechanical interfaces between CTM, target plant (divertor cassette) and environment were defined. Motion trajectories for divertor cassette handling were defined and loading conditions were estimated in the design specification phase. After that iterative concept design process was started. After the first draft of the CTM concept was modeled, divertor cassette handling was simulated and checked that no collisions with environment occur. Preliminary Finite Element Analysis (FEA) for the structure was done. After the results next design cycle was done. This was continued until concept design fulfilled requirements. [12] In the Figure 4, which has been taken from the DTP2 quality plans, this previous described process is presented for the additional end-effectors design development process.

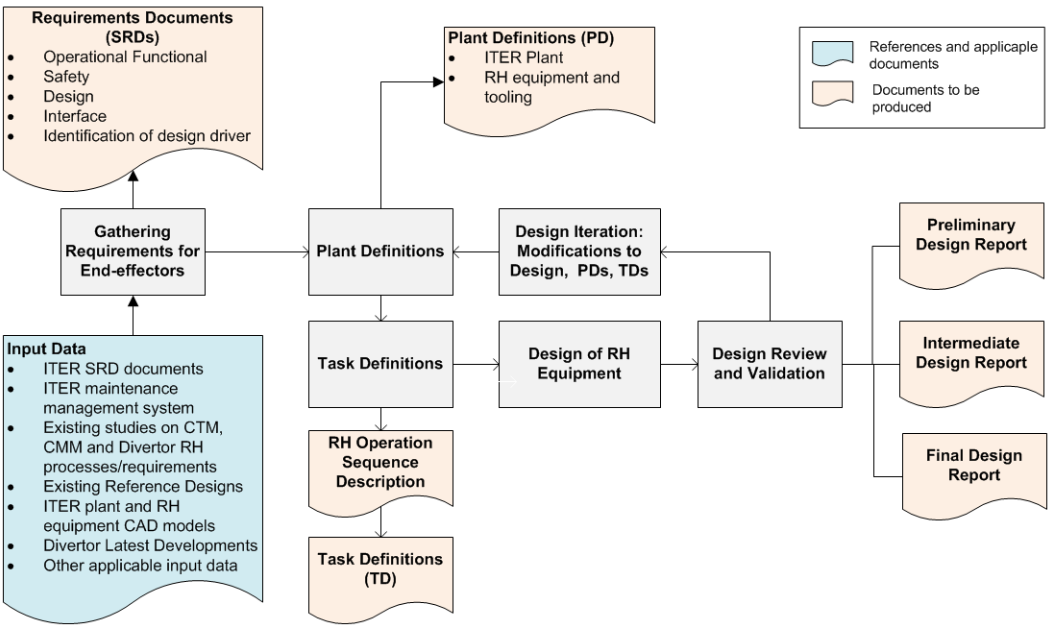

Figure 4.Example of DTP2 design development process

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Present DTP2 facility and PLM Architecture

Presently the DTP2 facility consists of Divertor Region Mock-up, Divertor Cassette Mock-up, Cassette Multifunctional Mover (CMM), Water-Hydraulic Manipulator, Control Software, Control Room and DTP2 Test Hall. Current main PLM architecture of DTP2 includes authoring and analysis tools (Dassault CatiaV5, Dassault SolidWorks), software development management system (Subversion SVN), electrical engineering design tool (Eplan), virtual reality software (Dassault Virtools), simulation and analysis software (Dassault Delmia), common office programs, a project management system and a document and quality management system.

Interviews and Workshops

PLM platform requirements specification was created collaboratively with the PLM end users during several interviews and workshops. The interviewees and workshop participants consisted of stakeholders from project management, system engineering, quality and information management departments, and representatives from different engineering disciplines and domains, i.e. mechanical engineers, software developers, electrics engineers, virtual reality and virtual prototyping experts, remote operation personnel, and testing engineers. The interviews and workshops were led by a PLM expert. The requirements specification document was used as basis for PLM supported system engineering platforms definition. Based on the requirements specification, a mechatronic product data model and needed PLM processes were defined and modeled using UML-language. The PLM –platform maps together PLM related requirements from relevant stakeholders and defines a concept how to harmonize product data and processes. It also forms a base for requirements related to a PLM –system architecture.

Product Life Cycle Support Standard

PLCS standard (ISO STEP AP 239) supports the product lifecycle management approach (Figure 5). There are also capabilities in PLCS that support system engineering approach. So called breakdown structures and relation between them support the system engineering method by utilizing functional breakdowns, system breakdowns, physical breakdowns, and actual product structure. [13]

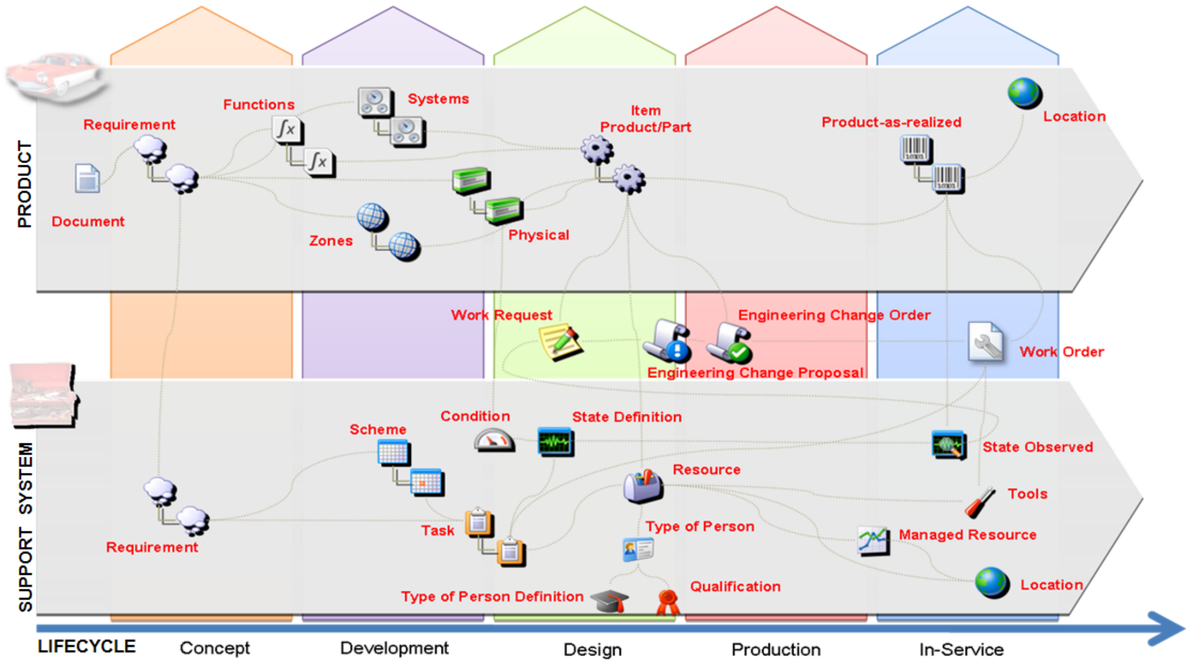

Figure 5. PLCS standard and terminology [13], [14]

RESULTS

System Engineering Platform Requirements

In Table 1 the main requirements for DTP2 system engineering support are listed. They are divided into general and DTP2 special requirements, as well as engineering domains based requirements. All requirements were gathered in DTP2 PLM platform interviews and workshops.

Table 1. Main system engineering support requirements

General PLM requirements	Item management, document management, structure and relationships Engineering change process management, change history, product information history management Product information related to different lifecycle phases is harmonized and centralized Harmonized management of product information Easy to access right and up-to-date product information Increased product information quality
DTP2 special requirements	Intelligent collaboration between different DTP2 engineering disciplines and stakeholders System engineering support Requirements management Virtual Models management: Virtual prototyping, VR, remote operation, product structures Manage the mechatronic product and the individual configuration of DTP2 and its maintenance process.
Mechanical and electrical design requirements	Intelligent management of 3D-CAD models, CAD –document revision and version management Support for E-Plan ECAD Support for ITER mechanical design metadata and formats
Software design and control room requirements	Subversion SVN integration support, relations to SRD and other domains Hardware and software configuration SW design authoring tools interface
System testing requirements	Test planning, system test sequences Relations to requirements and SRD documentation data formats
Project management and administration requirements	Project management and project documentation management support Project task breakdown relation to product structure model, project workflows support Relationships with F4E and ITER codes and naming policy, workflow Automated and smoothen the usage of reporting and deliveries

Mechatronic Product and Data Model

Product data model defines concepts needed to describe the DTP2 system. An item and item structure is used to represent one configuration of DTP2 or a part of a DTP2 configuration. In the PLM –system there exist a number of DTP2 design configurations needed for different purposes, e.g. conceptual design, new design or simulation design. Those designs have always a relationship to product individuals. The product individual is used to represent physical on-floor configuration of the DTP2. Both item and product individual configurations include up-to-date configuration as well as configuration history. An item i.e. design configuration can fulfill one or more required functionalities and those are defined with the functional breakdown –object. These object together with the document- and requirement –objects are mainly used to represent the configuration of DTP2 and relevant design information. Some of the object and definitions of required product data model are based on the ISO Product Lifecycle Support (PLCS) – standard (Figure 5).

Figure 6 presents one example of DTP2 Mechatronical Product Model. The Mechatronical Product Model includes the structure of DTP2 divided to Platform, Divertor Casette, WHMAN Manipulator, Remote Operation and CMM Robot. All these main modules of the DTP2 configuration are classified as Systems and are presented with an item and item structure. Both Main Systems and Systems are used to manage the whole Mechatronical Product Model of DTP2, so in other words they cross-over the boundaries of different engineering disciplines.

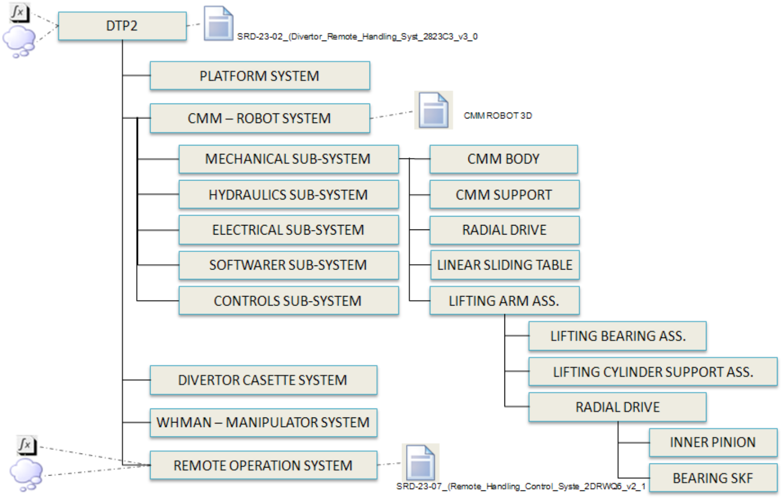

Figure 6. Conceptual example of the main DTP2 mechatronic product model

Supported System Engineering Processes

In order to meet the DTP2 system engineering requirements, PLM processes of Table 2 have to be supported:

Table 2. Supported System Engineering Processes

CORE PROCESSES	BENEFITS
Core Product Lifecycle Management	
• Mechatronics Product Process: Process to design and maintain the configuration of DTP2 Main System in collaboration with engineering disciplines in question. • Product Individual Process: Process to maintain the configuration of DTP2 Main System Product Individual in collaboration with engineering disciplines in question	• Increase the visibility and understanding of DTP2 Main System configurations between different stakeholders • Manage product data in a cost efficient way, • Boost the usage of existing design competencies, • Reduce costs by providing easy access to up-to-date product information
Smooth and Effective PLM Process Support	
• Design Process: Implement a more accurate, effective and automated Design Process • Engineering Change process: Implement a more accurate, effective and automated Engineering Change Process • Product Individual Maintenance Process: Manage the information and process to store information about maintenance and simulation tasks carried out.	• Better quality of product data • Product In-use maintenance history • Optimized collaboration processes with different stakeholders • Shorten development time • Cost efficient engineering change management • More accurate, effective and automated Engineering Design Process
Project Management and Delivery Support	
• Project Management process: Implement processes and tools in PLM –solution to manage project. • Publication and Reporting Process • Delivery Process	• Automate the project management process • Shorten project delivery and reporting times
System Engineering Process Support	
• System Engineering process: Implement processes and tools in PLM –solution to the system engineering process and related information.	• Automated and accurate system engineering process • Shorten project delivery and reporting times • Reduced cost by providing easy acess to up-to-date whole product lifecycle information

The system engineering processes will be supported by following core PLM system functions: Item and document management, requirement management, engineering change management, project and delivery management, project workflow management, product individual management, product in-use management. Some of the defined processes are based on the PLCS standard (Figure 5)

DISCUSSION AND CONCLUSIONS

DTP2 is a full scale mock-up and test facility for developing, testing and demonstrating remote operated maintenance equipment as well as planning and training future maintenance operations of ITER. It is a complex mechatronic system consisting of many engineering disciplines and domains, and special new technologies. Characteristic for DTP2 is that its development and operational lifecycle will be several decades long, and history of the system has to be traceable and all data must be available during the whole lifecycle. System engineering approach is applied in DTP2 development. It should be supported by systematic process and data management system, i.e. PLM.

System engineering is strong in multidisciplinary engineering and systematic chain from end-user requirements to functional requirements and finally technical solutions and validations. Design methodology supports System engineering by delivering more detailed technical solution alternatives. PLM should support these activities for instance with good requirements and engineering change management capabilities. On the other hand, PLM is strong both in product type and product individual data management. Those capabilities could be better utilized in system engineering. Obviously there is overlapping between System engineering, design methodology and product lifecycle management.

Bergsjö [9] and Abramovici [10] and have stated that currently PLM systems do not support multi-disciplinary development of a mechatronic system very well. On the other hand, Bergsjö has concluded that it is feasible to create an integrated information model for mechatronic development and implement it in a PDM/PLM system, although such PLM implementations for inter-disciplinary engineering are not yet reality in companies. The companies have though strategies moving in that direction. Anyway, Abramovici concluded that progress of future PLM models and implementations development will include better support for the whole product type and individual lifecycle, management of engineering support processes, multi-disciplinary engineering integration, and visualization of the product and process.

Esque [3] and Muhammad [11] have introduced special requirements for DTP2 development from software development and virtual engineering viewpoint. They have also proposed concepts and architectures for SCM-PLM integrations and digital mock-up model management in their research papers. Complete integrations of PLM and SCM are currently unavailable, but a suitable solution could be a loose integration between the two systems by using the APIs already built in these systems. They are good basis for further development of DTP2 system engineering support.

Purpose of this paper is to introduce the first results of the ongoing project which aims to define and implement PLM support for DTP2 system engineering. The preliminary results include requirements specification for the PLM platforms, and a concept for mechatronic product model and data model. The requirement specifications and the PLM platform were defined co-operatively with the end users (i.e. system engineers, project management and different engineering domains) and PLM experts. So far, it can be concluded that this liaison between engineering domains and a common understanding of system engineering requirements and PLM approach is essential for success. In the upcoming work, the PLM specifications and mechatronic data model will be further defined and implemented in IT-systems. Alternative PLM architectures will be studied and evaluated. DTP2 is good setup to study and evaluate the feasibility of PLM support for system engineering.

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