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Configuration management – a core competence for successful through-life systems engineering and engineering services

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Abstract

Through-life engineering services depend on capabilities to track and trace long-living systems and their components throughout the lifecycle. System configurations need to be known to (re)engineer, build, operate, maintain, and dispose systems in a sustainable way. Configuration Management (CM) is an approach to control system configurations with dedicated engineering processes, methods and tools – today foremost supported by information systems. This paper motivates CM implementation for through-life engineering services and systems engineering and related topics such as PSS (Product-Service Systems) and MRO (Maintenance, Repair, and Overhaul). CM fundamentals and related engineering activities are introduced briefly. Different CM views and daily challenges of CM for long-living complex systems are investigated. Software support for CM is discussed on the basis of PLM (Product Lifecycle Management) solutions. The paper highlights points that need attention for CM implementation (CM data and process management) by means of PLM. The paper summarizes requirements for CM based on PDM/PLM solutions, which are relevant for PLM solution vendors and for engineering companies and manufacturers moving towards PSS and MRO. The paper is written form an engineering perspective.

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Keywords: Configuration management; systems enginering; PDM/PLM; MRO; PSS

1. Introduction

Industry provides ever more complex solutions, which go far beyond an engineering and manufacturing of mass-produced standard products. This trend will remain as scenarios of intelligently networking, permanently interconnected, multi-modal energy and transport solutions indicate, cf. [1]. Customization of solutions has become usual for industrial business solutions and in end customer markets. At the same time, customers request solutions with high quality. Claims, e.g. in case of system deficiency or danger for humans, require information availability from engineering and engineering services. The more complex, customized, and often serviced a system becomes, the more complex is a tracking and tracing of system lifecycle information related to engineering tasks. Configuration Management (CM) is an approach to realize traceability of configurations of technical systems [2; 3]. CM is performed with different processes, methods, and tools in industrial practice. Although the need is clear in industry and not new, the implementation of CM is complicated and challenging companies in many branches.

1.1. Problem statement and motivation

Although CM is not new the expectations and requirements concerning its reliability and consistency become stressed seriously. The reasons are discussed in this paper. Anticipated in advance, data and process management based on current information management software systems need improvement and new concepts to enable efficient through-life systems engineering and engineering services in globally distributed engineering, system operation and maintenance.

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1.2. Research questions

In order to get deep insight into CM and solution approaches, the following research questions are used for the discussion in this paper:

- *Why is CM becoming more important in the future?*
- *How is CM framed from a theoretical point of view?*
- *What challenges information management for CM?*
- *What are the prerequisites for a lifecycle-oriented CM?*

1.3. Research approach

The approach is business driven. A systematic reflection of personal experiences collected in industry projects and an investigation of literature was carried out in order to align different personal views and domain specific interpretations of CM. The discussion was carried out by four senior engineers within the company, namely CONTACT Software, a PLM solution vendor. Two were experts in software engineering for information management solutions. One recently entered the company from a position in applied science on engineering design and MRO. Another had expert knowledge in industrial process design. All together were experts in information management and virtual product creation. Insights from aerospace, train and bus manufacturing, industrial solutions (energy systems), automotive (OEM and supplier needs), and software engineering floated into the discussion. Product creation and MRO both were systematically addressed throughout the investigations. The discussion was developed stepwise in workshops in order to collect views and to generate a systematic overview for influencing factors and a detailed picture of practical CM challenges. The driver was to develop a shared understanding of different business needs for future information management in general. This paper provides selected findings in a compressed form. It concentrates on the theoretical framework of CM positioned in an industrial context. It motivates further academic research about CM especially in the PSS and MRO research domain.

2. Rising importance of CM in the future

Globalization, accelerated innovation cycles, delivery within tough targets for "time, budget, and quality", emphasized sustainability, interdisciplinary engineering, and changing business models are generally influencing engineering design. This applies to CM as well. Anyhow, there are several specific reasons, which drive a need for a lifecycle-oriented CM approach. Major reasons are as follows.

Rising complexity (complex systems)

Technical systems learn, act autonomously and connect to other systems with intelligent algorithms, all based on innovation in logistics and ICT (information and communication technology). Industry solutions and end customer products integrate mechatronic sub-systems, embedded systems, or – in near future – cyber-physical systems [4]. Technical systems are distributed locally (e.g. wind energy turbines with smart metering installed in different locations) or used in changing settings (e.g. pooled e-cars). Realizing meaningful system configurations in engineering and operation is essential for technical feasibility, business success, safety, and efficiency.

Systems engineering (exploiting new capabilities)

Systems engineering [5-8; 2] has originated in the 1960s and was intended to manage complex engineering projects (especially aerospace and military projects). Computer support like today was not possible and even hardly imaginable. Today, systems engineering revives as it is now interesting to develop the broad spectrum of complex systems in many branches and because computer support provides amazing new capabilities. Technologies of virtual product creation support Model-based Systems Engineering (MBSE) including techniques for virtual design and simulation (validation and verification). System behavior can be simulated in multi-physical models before any physical prototype has been built [9]. This causes an increase of engineering data (partial and integrated product models), which need proper configuration to provide reliable simulation results.

PSS business and MRO capabilities

Different business reasons drive engineering companies and manufacturers towards services and business models integrating products and services systematically. Lifecycle-oriented business models based on systems/solutions integrating products and services are dealt with as Product-Service Systems (PSS). PSS business models focus on selling functionality, availability, defied results or capabilities [10]. MRO (Maintenance, Repair, and Overhaul) is framing capabilities to professionally sustain system functionality and availability by engineering services. Therefore, PSS and MRO meet each other in practice often times, for instance in the business segments of energy system or transport solutions (e.g. aerospace, rail solutions) [11]. On the one hand, PSS concepts support systematic information flows between product-service engineering and operation (delivery, use and MRO). This is vital to redesign PSS more systematically by use of field information but also for efficient MRO by use of engineering data (3D product models, spare part lists, drawings, etc) and recorded configuration information. On the other hand, consistent software support for an integrated product data and process management in engineering and MRO is rare. The information is often incomplete and distributed across several IT systems. Foremost, there is no consistent, lifecycle-oriented, IT-supported CM approach to track and trace system modifications (redesign, reconfiguration, repairs, etc.) continuously. This is a business limitation, which needs to be overcome for competition in PSS and MRO business.

Legal obligations and quality

In case of assumed insufficient product quality, companies may face claims of acquirers, end customers or public bodies. In order to defend against such claims, companies need to approve quality control (design validation and verification; service quality) in particular cases. In times of variant rich products and regular MRO service events, configuration management becomes a key competence to track and trace product configurations, development project documents, service protocols etc. It becomes a core competence to be compliant with standards such as ISO 9000 [12], APQP (Advanced Product Quality Process), CMMI (Capability Maturity Model Integration), CMII (Configuration Management II), or special regulations of bodies like the FDA (Food and Drugs Administration). Professionally applied, it even provides important data to apply techniques from Six Sigma and other process improvement approaches based on engineering KPIs (Key Performance Indicators).

3. Framing CM from different views

The targets of CM are reduction and management of complexity, reducing of cost, reuse of design solutions, and clarity of product and process data in engineering and MRO services at any time.

The major question is what CM is including in terms of engineering processes, methods, and tools. Furthermore, the influencing parameters need clarification to design a consistent CM approach, which is generic for application in all lifecycle phases and which is applicable to all types of required engineering data.

According to ISO standard 10007 [3], the following definitions can be provided:

A **configuration** represents interrelated functional and physical characteristics of a product defined in product configuration information.

A **configuration item** is an entity within a configuration that satisfies an end use function.

Configuration management consist of coordinating activities to direct and control configuration (concentrating on *technical and organizational activities*).

This is analogue to the configuration management after the NASA Systems Engineering Handbook. It says that configuration management controls system design states and tracks changes of performance, functional, physical, or non-physical characteristics of the system [2]. This view addresses two domains of CM: Firstly, the technical engineering domain, in which sales and design parameters of the solution are defined and configured. Secondly, the engineering management process to track changes of requirements, specifications and design solutions over time. After [13] this can be expressed as follows: "Configuration Management (CM) [is] a business process that enables an enterprise to manage what a configuration is supposed to be, including changes, and ensure that configurations, when completed, conform to their documented requirements." Both views are explained in detail in the following sections.

3.1. CM as an engineering management process

This process secures that product configurations and project documentation are transparent and traceable at any time during the engineering process of a complex system.

The most relevant requirement for this type of CM is to control the variance (dynamic changes) of the product and its engineering data (design documents, project documents, etc) over the time. Thus it is about variance in time, about relating product components to work tasks, and about identification of engineering documentation (product, process, and project) for chosen points in time. It is needed to provide approved data to get certified or to defend against claims.

Engineering chance management (ECM) [14] typically is interlinking CM processes with requirements engineering (i.e. requirements development and management), project management (i.e. with project processes) and with the generic development process (technical engineering process). CMII certification, for instance, can be one way to approve these processes in compliance with quality management processes. "CMII [is] a business model for an integrated process infrastructure that can accommodate change, keep requirements clear, concise and valid, ensure that work results conform and avoid the need for corrective action" [13].

3.2. CM as a technical engineering process

In the main engineering process, the core process, engineers work with design parameters of products. They deal with characteristics such as power, weight, efficiency, material allocation, etc. They implement properties such as "sportiveness" or "robustness", for instance for vehicles, and realize features e.g. for comfort or safety.

In different process phases, the engineers apply different perspectives, methods and tools to fulfill this task. The following paragraphs explain three perspectives.

3.3. CM perspectives along the system lifecycle

Custom-tailored or custom-configured systems with long lifecycles typically have a high degree of variance. "Open configurations", where a customer takes a set of standard modules plus individually engineered extensions (process solutions, extended features, and specific interfaces) are state-of-the-art for investment goods (production equipment, energy and transport systems, process industry). Individual or single-item production is a consequence of order management strategies such as "Configure to Order", "Engineer to Order" or "Make to Order". To manage configuration changes, plan design verification, calculate engineering cost etc., configurations need to be transparent [CF. 11; 2, SECTION 6.5].

Furthermore, many reconfigurations are made during MRO events in the system lifecycle. The cause is reengineering/redesign performed to adapt the system to changed needs, or to repair or upgrade the system. Configuration management is important to identify "as is" configurations as far as possible, in order to plan and execute MRO events which are often carried out as technical services.

In that sense, literature uncovers three main topics of configuring products and product data in a broader scope: All three issues are relevant in industry and appear along an engineering and system lifecycle. How these are named in particular in practice is often depending on the company, domain etc. In general, these three topics of CM can be clustered as:

- *Customization* (configuration of product features; from sales to engineering; closed and/or open configuration; inner vs. outer variance)

- *Variant management* (application of build rules; valid product composition; modeling of variability to generate configured product variants / product configurations; design strategy)

- *As-built management* (tracking and tracing all reconfigurations; collecting of as-is data and documents describing the product and its context; managing variability over time)

Customization

Customization is an approach to offer customer-oriented solutions. Closed configurations are applied for products aiming at consumers (e.g. notebooks) or end users (e.g. cars). Closed configurations are feasible for products with high take rates and a high degree of pick-to-order or assemble-to-order manufacturing and delivery strategies. The product can be configured within a defined solution space including a completely defined set of solutions or solution rules (which might end-up in a vast variety of potential product configurations anyhow). For these products, "all configurations" (or at least reliable reference configurations) are approved in the engineering process, which come before customization in a sales process.

A different situation is given in engineering-to-order approaches. Engineer-to-order is daily practice for instance for aircraft, train, bus or truck manufacturers. All these systems are highly customized at the beginning of customer projects, but there is typically an open solution space. The basic engineering is done before customer projects start, but it is not possible to anticipate or model all solution variants (configurations) of a system during the basic engineering. The reasons are manifold:

- The detail engineering is part of customer projects.
- The basic design has a high inner variance so that not every potential solution can be designed to an end before an order. (E.g.: positions of seats and handles in busses.)
- Design approval efforts may be too high for frontloading.
- Small series or "one-of-a-kind" product: not all potential configurations need approval.
- The customer provides own equipment to be integrated (e.g. seats for aircrafts or ticket systems in busses).
- The supplier is providing updated components regularly.
- Not all thinkable configurations can be modeled reasonably.
- Customization as business justification
- …

Variant Management

Variant Management (VM) is applicable to systems, which have by intention a certain degree of configurability based on platforms, modules or standard components. For instance, the cockpit in a car today always includes a wheel to steer the car. This wheel can have extra features such as buttons to control the radio or telephone, leather surface or smaller diameter in sports variants. In general, there is a dedicated room of configurability and most configurations or at least packages are approved to a practically acceptable degree (closed configurations). Not all potential configurations can be approved because of combinatorial efforts. Anyhow, for some products, basic configurations are extended with special design solutions for extended components (open configuration).

The idea is to generate a high outer variance of products based on standardized modules developed and tested in advance. Variant management also offers possibilities to upgrade products etc.

Anyhow, variant management needs to meet the following requirements:

- The configured products need to be valid in terms of functionality and manufacturability.
- This means, avoiding contradictions of impossible configurations (tracing contradictions) is important.
- Completeness checks should enable designers to identify missing components.
- Quick calculations of design parameters (e.g. sum of masses, geometric parameters of configured solution) should be enabled.
- Easy definition of configuration of rules and sets
- Swift generation of lists, structures and documents describing the configuration (e.g. manufacturing BOM, service BOM, component structure).

As-built management

Systems with high investment cost and long life cycles (e.g. energy and transport systems) require MRO (Maintenance, Repair, and Overhaul) to large extent. MRO of such systems often means reengineering of components or structures in MRO events and therefore searching and generating engineering data and documents (e.g. drawings, calculations, service BOMs). The main issue is document management, as "simple" documents such as TIFF or PDF files contain information about MRO orders, project execution (MRO projects often consume months) or particular designs and design modifications in manufacturing, installation and ramp-up (often documented by redlining in printed files). Anyhow, working on original 3D models etc. eases reengineering.

Tracking and tracing all modifications (of documents or CAD/CAE models etc.) is the core task of configuration management in the sense of as-built management. This is because the documents (more or less precisely depending on varying data availability) describe the design of the real system. This type of CM is therefore focusing on managing the variability of the documentation over time. It is analogue to document management in product development and applies to product data, process, and project data (information about orders etc).

At least, there are several major release states that are covered by this CM process, comparable to those used in MRO for steam turbines [15]:

- *as planned* (as offered and as ordered, e.g. based on customer needs)
- *as engineered* (application of build rules; tracing approved revisions)
- *as built* (realized configuration, installed configuration)
- *as approved* (configuration to be operated)
- *as maintained* (maintained technical system)
- others … (e.g. tracking of component disassembly and remaining life limits)

Finally, experience shows that the documented configuration might differ from the actual system configuration. Operators or MRO service providers take over maintenance tasks but do not own digital product data of the technical system. OEMs hold information back in order to protect their IPs or to offer MRO services on their own. Long product lifecycles complicate availability and compatibility of digital data and technical support. A verification of the actual against the specified configuration is often intended and becomes more difficult if no configuration management is performed [16; 15]. A CM process should enable a convenient base-lining, effective search and document orchestration for reengineering and delta analysis between the base-lined configuration and the state captured in the field (e.g. by means of 3D measuring techniques or condition monitoring).

4. Information management for CM

The previous section showed that CM runs on engineering data recorded in any kind of document (such as specification documents, design models like 2D drawings, 3D CAD models or logic plans etc.) and meta-data (i.e. revisions, versions, author information). In general, it is recommended and common practice to manage this kind of data in PDM systems and PLM solutions.

PLM (Product Lifecycle Management) is an integrated management approach: It brings the product data from the different steps of the product lifecycle systematically together. It consists of a consistent set of processes, methods and tools to manage product information throughout the entire lifecycle. It is not limited to single enterprises, but addressing collaboration networks and supply chains [17].

PDM (Product Data Management) is an approach for efficient data management especially for engineering tasks. It is a possible technical basis for PLM processes. It originated in product creation but meanwhile receives more attention for engineering tasks in MRO. The core functionality is data and process management. Like ERP (Enterprise Resource Planning) systems, PDM system typically base on databases.

In general, PDM systems already provide useful features to implement CM solutions. Some of the most relevant features are: versioning of documents, revisioning of product structures and included documents, variant management tools, workflow management (e.g. for ECM), requirements management and project management. Nevertheless, there is no standard up to now, which covers the perspectives of the *technical engineering process in CM (i.e. customization, variant management and as-built management)* within one consolidated *engineering management process for CM*.

5. Prerequisites for a lifecycle-oriented CM

The engineering use cases related to CM (cp. Tab. 1) need to be clarified before a CM approach can be defined in a company. Furthermore, today CM data is often distributed in PDM, ERP, and MRO planning systems and often incomplete. A critical analysis of the IT landscape (or at least IT processes) is recommended in order to pave the way for CM. The model of variability (needed for customization and variant management) probably needs to be revisioned entirely after major changes and approval. The same applies to every documented modification of the physical system. ECM (Engineering Change Management) is probably required to interface between the technical part and the management part of CM and to interface other management processes (see above).

Table 1. CM views (brief summary, simplified views).

CM domains	← *CM as engineering management process* → [managing configuration changes over time from a process perspective]		
	← *CM as technical engineering process* → ["designing variability", defining feasible configurations changing over time]		
CM perspectives along the system lifecycle and engineering process	*Customization*	*Variant management*	*As-built management*
	[managing variability of the solution space, i.e. managing variance of design parameters]		[managing configuration changes over time]

(Finally, it is recommended to investigate cross-effects with standard catalogues and effectivity control, which both are out of scope in this paper.)

6. Conclusion and summary

The competence to control and manage engineering processes of complex systems is an extremely important competitive business asset of companies in developed industries such as in Germany. Manufacturers offer cutting edge technology and customized solutions globally in complex projects for development, installation, ramp-up, operation, and supporting services. Changing types of business models require transparent views of information about system states or the competence to generate this information efficiently, e.g. in case of MRO events.

It is clearly tough engineering business to manage all data needed to track and trace system configurations throughout countless MRO events of complex systems. Data management solutions are vital to master this challenge. As many MRO events include reengineering (e.g. of aircrafts, trains or industrial solutions), product data such as drawings, BOMs (Bills of Materials), 3D CAD models or manufacturing and maintenance instructions need to be changed regularly. In product development, this type of data is typically managed in PDM systems. For lifecycle-oriented systems engineering, PLM solutions are recommended, but most companies have difficulties in deploying true PLM solutions spanning product development and MRO service at the same time. Different departments, different work practices and document lifecycles cause trouble for PLM solutions. Nevertheless, reengineering is part of MRO business and applying methods similar to product development. One difference is that it is somewhat "more document- and less CAD-driven".

Finally, there are three major prerequisites to overcome this obstacle:

- *Firstly, a shared understanding and engineering transformation to meet CM in practice.*
- *Secondly, a consistent lifecycle-oriented CM concept, which is capable to integrate all CM views from Tab. 1.*
- *Thirdly, a PDM-based platform implementing the CM concept in order to maintain engineering tasks and PLM throughout the entire system lifecycle.*

These prerequisites apply to manufacturing companies moving to PSS and MRO. At the same time they demand enhanced solutions from PLM vendors. CONTACT Software, for instance, is addressing this need and provides customers with PDM/PLM applications to master particular challenges related to CM. Finally, the implementation of industrial CM standard is still ongoing and requires research and consolidation.

To conclude: True Lifecycle Engineering (LCE), integrating the views of systems engineering, PSS, and MRO, depends on a successful implementation of configuration management and PLM support.

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