White Paper

PLM: Future IT Architectures in Engineering

prostep ivip White Paper

PLM: Future IT Architectures in Engineering

Requirements – Technologies – Approaches

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Standardization Strategy Board

Abstract

This white paper focuses on the design of future PLM IT architectures against the backdrop of current trends in product and system development. It first of all examines these trends with the aim of determining the key components, the technologies and the framework conditions needed for their implementation and operation. This is followed by a presentation of existing approaches and new areas of activity relating to the design of future IT architectures for product development.

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1 Introduction

The term product lifecycle management (PLM) is understood today to mean very different things and is often incorrectly reduced to merely an IT system. PLM is defined as a concept for managing a product, including the associated intellectual property, throughout its product lifecycle. In the context of realization, it includes processes, organizational structures, methods and supporting IT systems. This holistic approach has the potential to profitably structure and align companies in the face of the competition, as well as integrate and motivate employees as a key element. All the departments in a company that are related to the product and to the associated processes and resources are included. The objective is to ensure that all the elements involved work in perfect harmony in the different domains and across different locations through the product lifecycle [DSU-11].

The PLM IT architectures created for product lifecycle management are therefore made up of a large number of individual IT systems. In addition to domain-specific authoring systems, these also include domain-specific data management systems, overarching backbone systems and enterprise-wide ERP/MRP systems. These IT system structures have usually already been established in the companies. Against the backdrop of current trends in product, system and service development, however, the question arises as to whether or not these structures will remain adequate in the future and how IT architectures in product development can evolve to meet future requirements and challenges.

Relevant trends here include the development of highly-automated and autonomous systems and further expansion of cross-enterprise and, in some cases, cross-industry collaboration. The establishing and use of cross-enterprise collaboration platforms as well as the issue of data security and confidence in data and information (digital trust) also play an important role when it comes to collaboration. An extremely important trend that has the potential to make a significant impact on the design and use of IT architectures in product development is an expanded understanding of data, information and knowledge and a corresponding change in access to data, information and knowledge in the context of product development. The potential offered by the use of metaverses has recently been the subject of much discussion. This trend could also give rise to new requirements and challenges relating to the design of future IT architectures in product development.

The prostep ivip Standardization Strategy Board (SSB) project group has examined the question of whether or not the IT architectures established in product development today will be able to meet the requirements and challenges of the future. This also raises questions as to which components in established IT architectures still have a future, where changes and adaptations are needed, and where entirely new areas of activity will emerge in the context of IT architectures in product development.

The SSB is a project group initiated by the VDA and organized by the prostep ivip Association. It addresses issues relating to the need for standardization in the context of cross-company collaboration in product development and manufacturing. The SSB also picks up future-orient trends in product development and attempts to address the resulting cross-enterprise challenges in committees and specialist groups.

2 The impact of product development on future PLM architectures

Product development has always been shaped by the latest social and technological trends. These trends are also reflected in the requirements relating to the digital environment for product development. This means that it is important to provide a clear picture of these trends. The following topics have been selected as examples:

- System complexity
- Pressure to innovate
- ESG (environmental, social, and corporate governance)
- Demographic change / shortage of skilled workers

Increasing system complexity is a long-term trend that is being further accelerated by the dynamic digitalization of product worlds. The processes, methods and tools in product development need to keep pace with this development. It is particularly important that the merging of software and mechanics into systems be mapped and that the associated and very different development processes be linked with each other. At the same time, the expected system functionality is also becoming increasingly complex, as exemplified by the topic autonomous driving. New, fully automated test procedures are needed if requirements relating to system release are to be met.

A new trend is the strong dominance of ESG objectives in the areas environment, social affairs and corporate governance for economic actors. These factors have been a key topic in manufacturing industry ever since the relaunch of the conference calendar following the huge break imposed by the coronavirus pandemic. Product development must also be geared to these objectives. A recent example of the impact that ESG objectives is having on product development is the proposal for a Regulation of the European Parliament and of the Council on batteries and waste batteries [EUR-20].

These challenges have to be mastered by a dwindling number of available skilled workers and specialists. The demographic change is now so far advanced that its impact is clearly being felt. This too is a global issue with slight differences between countries. However, the direction in which this trend is moving is the same everywhere, especially in industrially highly-developed countries.

In addition to these social and cross-market topics, there are other trends worth mentioning that will also have an impact on future PLM architectures. These are:

- Model-based definition
- Cross-enterprise collaboration versus the decoupling of business units
- Seamless access to data, information and knowledge
- Industrial metaverses
- Security and digital trust

In the following sections, we will discuss their impact on future PLM architectures.

2.1 Model-based definition

Over the course of the last two decades, model-based engineering (MBE) and model-based definition (MBD) have become established in the context of developing complex products and systems. In the case of model-based definition, the subsequent product, with all its properties, is developed in its entirety in (parameterized) models. Model-based definition, however, goes far beyond modeling the product as such. In model-based definition, the model provides the starting point and basis for almost all downstream processes, such as development processes, validation processes, production and production planning processes, documentation processes and, to an increasing extent, also approval processes and maintenance processes like predictive maintenance. The model is also ultimately the key factor when it comes to the virtual product experience.

The models created in this context can be extremely varied and also domain-specific. In their entirety, however, they map not only the geometric shape but also every property and behavior of the product with the desired and necessary level of detail and accuracy. The challenge posed by model-based definition lies in creation, linking and use of the models. However, the linking and use of the models in particular requires efficient management of the models, including the management and provision of knowledge relating to the models. This means that model-based definition has a very significant impact on the design of IT architectures in product development. Model-based definition is not just an internal company issue. Model-based definition requires a cross-enterprise approach, and the exchange and joint use of development data across company boundaries is a key challenge when it comes to functional design in the context of cross-enterprise collaboration. The following section focuses on what shape this collaboration can take.

2.2 Cross-enterprise collaboration versus decoupling

In the context of cross-enterprise development collaborations, establishing and organizing the development partnership at engineering level is not the only challenge that the collaborating companies face. The termination of a development partnership also poses technical and organizational challenges. The following section takes a closer look at both these aspects.

2.2.1 Cross-enterprise collaboration

Collaboration across company boundaries is becoming increasingly important for the success of innovation and development projects. Products (e.g. vehicles) are being created to an increasing extent within the framework of new partnership models – collaboration between teams from different companies is now a must. Collaboration means working together on a task and achieving common objectives. Two or more people or organizations work together with the aim of sharing knowledge or solving a problem. Business collaboration encourages social interaction both internally and externally, crowdsourcing and a new level of collaboration between different parties, be it employees working on the same project or customers and suppliers working together to solve a problem. Faced with the pressure of increased competition, shorter product lifecycles and increased risk, companies today recognize the benefits of temporary partnerships. Different types of collaboration (OEM/supplier relationship, strategic alliances, innovation networks all the way through to co-creation ecosystems) give rise to different forms of collaboration.

2.2.2 Decoupling

Integration and consolidation were for a long time the main challenges that needed to be tackled in the context of designing PLM architectures and landscapes. The ability to integrate and the availability of solutions for efficient collaboration within companies and across company boundaries were major drivers in the PLM context.

In contrast, the various crises in recent years mean that the ability to make business processes less susceptible to the impact of national legislation, geostrategic measures and crisis situations has become increasingly important.

The requirements relating to collaboration and decoupling, which at first glance seem contradictory, need to be taken into account when designing state-of-the-art IT architectures. This is because modularity, semantic definitions and the widespread use of standards also provide a means of coping with decoupling requirements. Typical examples of the objectives behind decoupling strategies include:

- Reducing dependence on foreign countries and companies
- Facilitating dominance of the domestic market by domestic companies
- Leveraging domestic dominance to increase competitiveness on the global stage

Information technology tools and resources are increasingly being used to achieve the objectives listed above. For example, the legislation in different countries includes regulations and specifications for the transfer of data across national borders. If due consideration is to be given to the resulting measures and restrictions, this requires, for example, that specific gateways, filters or concentrators be set up in PLM architectures to ensure that lifecycle-related product information can be used worldwide. In some cases, they also require processing and storage within national borders.

National standards are also used as tools for implementing decoupling strategies. In conjunction with limited access to national standardization bodies and the associated (delayed) access to information, this can have an impact on, for example, the functional scope of PLM components (supported formats, process, etc.) and thus require local differentiation through to and including the predominance of local providers.

Requirements relating the origin of infrastructure and network components, as well as the availability of telecommunications services, can also have an impact on the structure and design of PLM systems.

2.3 Data, information and knowledge

Data, information and knowledge are three key elements of data management. However, these terms are often not clearly defined and are therefore used in ways that can easily be misunderstood. Systematic use of these terms is essential if the challenges posed by comprehensive data management are to be met. A brief introduction to the three terms is provided below and highlights their unique characteristics. Data, often referred to as raw data, are individual facts that have no immediate meaning and are difficult to understand by themselves. Data in context, on the other hand, are individual facts that have meaning and can be readily understood but do not yet constitute information. They become information when they are of relevance to one or more people at a certain point in time. Knowledge, on the other hand, is information stored with an understanding of the meaning of that information that has been acquired through experience, awareness or comprehension.

The data-information-knowledge cycle is the cycle from data, to data in context, to relevant information, to knowledge, and back to data when that information or knowledge needs to be stored again. The stored information and knowledge thus become part of an organization's data resources and are managed in accordance with formal data resource management concepts, principles and methods.

Conventional data science methods can convert raw data into information. Machine learning can help extract knowledge from information. Machine learning algorithms find context in information by recognizing patterns, grouping information or classifying information. That is why data is a valuable asset for companies – it is able to reduce the time, effort and resources needed to solve problems and make informed decisions.

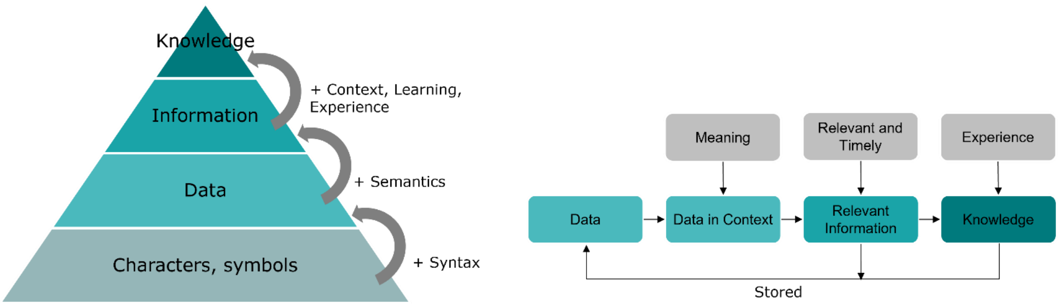

Figure 1: Knowledge pyramid[1] and data-information-knowledge cycle[2] as the basis for enterprise data management

2.4 Security and digital trust

IT security and digital trust are aspects that are becoming increasingly important due to the growing volume of information, its scope and quality, and the growing number of processes in PLM applications that use this information, which is already high.

2.4.1 Security

The continuous further development of PLM applications, from team data management platforms to widely used systems with backbones, digital twins, data analytics portals and other functionality, calls for additional approaches to maintaining IT security and minimizing the risk of cyberattacks. At the same time, the attraction of PLM platforms for hackers is steadily increasing due, on the one hand, to the growing volume of information they contain and, on the other hand, to the increasing complexity of IT architectures and thus their vulnerability.

Striking a balance between the democratization of data, i.e. making access to data as easy as possible, and the increasing risk of data misuse poses a considerable challenge in practice. In combination with the use cases and the volume of data that requires different levels of protection, the mapping of these requirements in

[1] Based on North's knowledge staircase, http://www.north-online.de/
[2] See https://www.dataversity.net/the-data-information-knowledge-cycle/

conventional, role-based authorization technologies in this context is reaching its limits in terms of feasibility and maintainability.

Collaboration with partners across company boundaries increases the need for action. The challenges posed by collaboration are often met with organizational measures. These require individual coordination and regulation efforts in advance as well as additional time and effort for implementation. Both have a negative impact on efficiency as a result of time lost or additional time and effort required and adversely affect the desired economies of scale.

Cloud scenarios and Internet-facing operating concepts place further demands on the security of PLM platforms. Whereas third-party products, extensions or interface components of a PLM solution were previously operated on premise in an environment monitored in-house, all the components of a PLM landscape – without exception – must meet the required security standards when exposed to the Internet.

2.4.2 Digital trust

PLM process chains link data sources and data sinks across different phases of the lifecycle. This and the automation of such process chains in particular requires agreements between data producers and data users.

From the data users' perspective, aspects such as content, scope, recency, quality and availability are crucial requirements when it comes to implementing solutions. Typical aspects from the perspective of data providers are authorship, time and effort required for creation and maintenance, monetization and, for example, liability.

Both perspectives highlight the need to obtain additional information that goes beyond the "raw data" and allows conclusions to be drawn with regard to the above-mentioned properties and thus making it possible to assess the risks posed by using the information.

If we project this onto cross-enterprise PLM scenarios, this requires not only the level of transparency demanded above in the form of a digital metadata "package slip" but also additional capabilities to digitally secure the reciprocity of the expectations, to provide proof if necessary and to protect it against manipulation if necessary.

Error! Reference source not found. provides a graphical representation of this interrelationship.

Figure 2: Digital trust from the customer's perspective

This reveals the need for consensus mechanisms between the partners collaborating in PLM. Important consensus-related aspects and perspectives include:

- Technical consensus: e.g. architecture and solution patterns used, interface standards and formats.
- Procedural and process-related consensus: e.g. agreement on workflows and sequences, responsibility for content and where responsibility starts and ends, status networks, intended use
- Data and data quality: data models, glossaries, ontologies, data quality criteria and their evaluation
- Commercial consensus: monetization, copyrights and rights of use, commercial exploitation
- IT security: security against theft, misuse, manipulation and interference by third parties, use of standards and application of principles
- Ethical consensus: agreement on common ethical principles, i.e. climate goals, human rights, health

In the context of future, collaborative cross-enterprise PLM constellations, this means that, in addition to the technical challenges, there is also a need to support transparency and consensus-building by means of appropriate capabilities in the PLM architecture.

3 Review of current PLM IT architecture concepts

Historically, the 4-layer PLM model is a further development of discipline-specific TDM approaches. It spans a fourth layer, the federated backbone, as a horizontal bus over the participating disciplines, linking them with each other. This means that all engineering work products are managed as a whole in a cross-discipline product structure. Capabilities such as baselining and change management can be addressed in an overarching context. The backbone also often serves as a single source of truth for downstream processes.

The vast majority of PLM implementations created in this way work in a document-oriented manner. In other words, they manage work products from the discipline-specific vertical silos (e.g. mechanics, simulation, electronics) in containers described by metadata.

The requirements of model-based engineering, however, are placing new demands on PLM architectures that cannot be met with the possibilities offered by the document-based approach. End-to-end data flows in a model-based world go hand-in-hand with the ability to reference and influence individual aspects of the data. Document-centric approaches, however, do not typically refer to the content of the managed document and instead act on information provided by descriptive metadata.

This requires extensions for semantic data definitions (models), access to model-based aspects (APIs), the management of ontologies and other functions.

Figure 3 shows a typical example of a conventional PLM architecture.

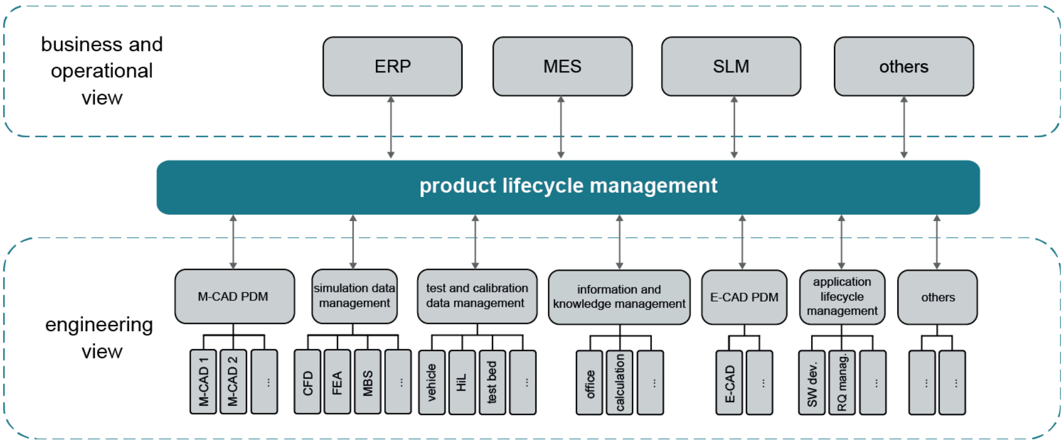

Figure 3: PLM as a platform for linking development and business data [ZAD-21]

4 State-of-the-art IT technologies as enablers for future PLM architectures

As described above, PLM architectures have already found their way into companies, but these architectures are predominantly document-centric. They also offer numerous functionalities that will, of course, also be relevant in the future. Making no claim to completeness and without, at this point, expanding on the definition and deeper understanding of the capabilities, these include change management, collaboration management, configuration management, long-term archiving, product data management, requirements management, simulation data management, task and workflow control, test data management, variant management and xBOM management. At many companies today there is also integration of, or at least interaction between, the PLM and ALM worlds, with the aim of taking account of the increasing importance of software components for product and system functionality and thus also of software development as an integral part of product and system development.

However, given the trends in product development mentioned earlier, these PLM capabilities can be improved. Depending on the capability in question, this could involve improving performance, improving quality, better integration between domains, reduction of effort involved or other improvements. These improvements can be achieved through the use of state-of-the-art basic technologies. These basic technologies, which are explained in more detail below, are primarily aimed at a more refined handling of data, information and knowledge. They can be considered as new or improved enablers for enhanced PLM capabilities.

4.1 Artificial intelligence, machine learning and neural networks

Artificial intelligence (AI) is a branch of computer science that deals with the development of intelligent machines that can think and act in the same way as humans. AI can perform tasks such as visual perception, speech recognition, decision-making and translation between different languages. AI has become firmly established in many industries, from healthcare to finance, and is being used to automate processes, increase efficiency and make more accurate predictions. AI uses techniques like supervised and unsupervised learning, deep learning, natural language processing and expert systems to enable machines to learn from data and improve their performance over time. Machine learning is a branch of artificial intelligence that focuses on the development of algorithms and models that can learn from data, recognize patterns and make predictions without being explicitly programmed to do so. It has become firmly established in numerous industries, including healthcare, finance and marketing.

Applications involving machine learning and artificial intelligence in the development of automotive products include autonomous driving, predictive maintenance, vehicle diagnostics and traffic forecasting. In the case of autonomous driving, for example, AI is used to recognize objects in the surrounding environment and make decisions about how to navigate a vehicle safely and efficiently. Predictive maintenance uses AI to identify patterns in vehicle data and gain insights into when maintenance should be performed. In the context of vehicle diagnostics, AI is used to analyze vehicle data to identify potential problems. Traffic forecasting use AI to predict traffic patterns and help drivers plan their trips accordingly. In addition, machine learning can also be used to identify patterns in customer behavior and make predictions about the future market.

The biggest challenges when it comes to AI and machine learning are scalability, data accuracy and data protection. Scalability because machine learning algorithms often have to process large amounts of data, and data accuracy because algorithms need to be trained with accurate data if they are to make accurate predictions. Privacy also poses a challenge because machine learning algorithms can be used to access sensitive information. In addition, machine learning algorithms can be difficult to implement and require special skills and resources. In this respect, the potential that AI and machine learning offer in PLM architectures lies in improving the accuracy of product data, automating processes and optimizing product designs.

AI, machine learning, and semantic networks: all these three technologies use mathematical functions (artificial neurons) to detect patterns in data. In this context, AI is capable of making intelligent decisions, machine learning can automate processes, and semantic networks can represent data in a more readily understood format.

4.2 Semantic networks and ontologies

A semantic network is a method of knowledge representation that uses a network of interconnected nodes to represent the meaning of a concept or object. The nodes represent concepts or objects, and the edges represent the relationships between the concepts. This network is used to represent semantic relationships between different concepts, providing a more robust understanding of the world. Semantic networks can be used to represent natural languages, classify objects in an image and identify the relationships between objects. Well-known applications involving semantic technology include natural language processing, search engine optimization, information retrieval and automated decision-making. Natural language processing uses semantic technology to interpret natural language input and generate responses. It the context of search engine optimization, it is used to refine search queries. In information retrieval, semantic technology is used to search large databases for relevant information, and in automated decision-making, it is used to identify patterns in data and make decisions without human intervention.

In the automotive industry, semantic networks are used for automated feature engineering, automated defect detection and automated object recognition. Automated feature engineering uses semantic networks to automatically identify and extract relevant features from raw data. In automated defect detection, they are used to identify defects in parts or components, and in automated object recognition they are used to classify objects in images and videos.

Ontologies are also used in addition to semantic network. The main difference between ontologies and semantic networks is that ontologies are more formal and structured than semantic networks. Ontologies are used to create a machine-readable knowledge model, while semantic networks are used to represent relationships between objects. Ontologies are also used to enable data integration and exchange between systems, while semantic networks are used to represent the structure of a particular system.

Ontologies are used in a large number of different domains, including natural language processing (NLP), knowledge representation, artificial intelligence and biomedical informatics. They are also used to create semantic web applications that allow machines to better understand the meaning of web content. Ontologies are also used in enterprise systems to facilitate data integration and exchange between different systems. They are used in product development processes to enable efficient data integration and sharing. This allows product teams to create a common language and structure for data, which makes data interoperability between different systems easier. In addition, ontologies can be used to improve the accuracy of data analysis and decision-making and to gain insights from data so that product teams can understand customer needs better and develop products accordingly.

Several RDF schemas are already being used in the automotive industry. For example, the Automotive Ontology[3] is a domain-specific ontology used to organize automotive data. In addition, the Vehicle Ontology[4] is used to represent information relating to vehicles, including their parts and components.

While artificial intelligence, machine learning and semantic networks describe how information and knowledge can be generated, organized and made available in the future, cloud and cloud-based methods describe a technical and methodological infrastructure in which data can be stored and made available to a larger group of users. This is discussed in the following section.

4.3 New PLM software technologies

Software technology has changed drastically since 2000, primarily due to the impact of the Internet. Away from the monolithic aircraft carrier and towards the federated flexible frigate (→ Cloud, REST[5], RDF[6], WEB services, micro services). This trend continues to grow. One unanswered question is what does an optimal architecture look like? A central core with distributed and linked applications, completely decentralized with multiple cores or a hybrid solution?[7] shows an open PLM architecture as a semantic federation layer that leaves it up to the user to decide which functions are linked in the PLM core or via linked data.

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[3] http://www.automotive-ontology.org/ online 09.02.2023
[4] https://enterpriseintegrationlab.github.io/icity/Vehicle/doc/index-en.html online 09.02.2023
[5]Representational state transfer (REST) refers to a programming paradigm for distributed services, in particular web services
[6] The Resource Description Framework (RDF) is considered a fundamental component of a modern data model
[7] Oleg Shilovitsky, http://beyondplm.com/2020/10/03/learn-why-decentralized-version-of-truth-is-thefuture-plm-paradigm/

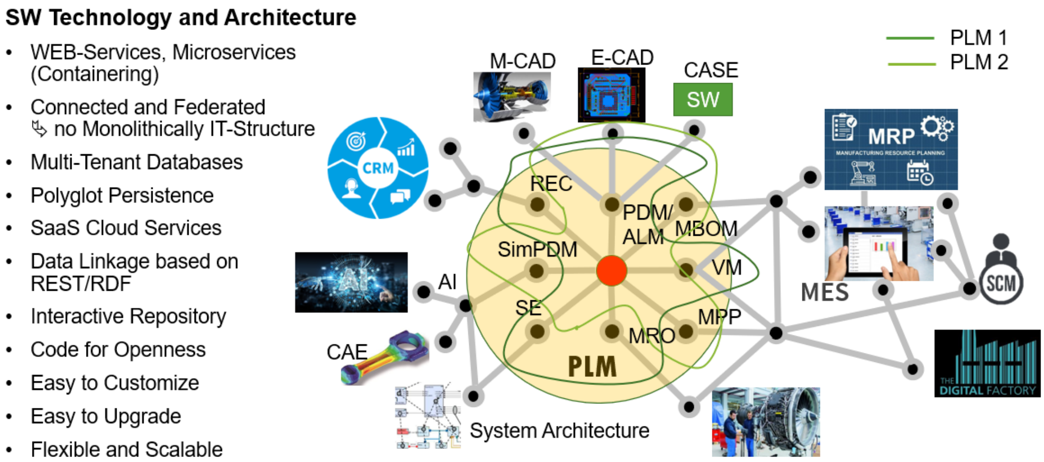

Figure 4: PLM as an open semantic federation layer and the corresponding SW technologies [Eig-21]

Scalability in the cloud will become a major management issue. It is difficult to predict the growth rates of applications, storage capacity usage and bandwidth. A distinction is made between vertical scaling (→ adding resources) and horizontal scaling (→ scale out is usually associated with distributed architectures). The latter usually requires major changes in programming technology8. For many PLM systems, this will mean reprogramming of at least part of the system. Horizontal scaling is a must for PLM [PRH-22]. Additional software technologies are required (→ microservices, containerization, convergent and hyperconvergent systems) if the aforementioned elastic scaling (→ vertical and horizontal,) and thus performance and optimal deployment in cloud solutions, is to be achieved. Microservices architectures will become the foundation upon which digital workloads and future system landscapes are developed. The convergence of container technologies such as Docker and scalable cloud infrastructures makes it possible for the first time to design, develop and operate system architectures that promise not only maximum agility and scalability but also robustness.

PLM providers have been working with relational databases for years, and this has also proven successful for standard functionalities. PLM functions, e.g. visualization, evaluations, exist for which parallel NoSQL databases, e.g. Graph DB's, are suitable (→ Polyglot / Multi-Tenant DB's). Time series databases, which have been developed specifically for monitoring mass data from measured values provided by feedback from sensors, are perfect for IOT/IOS applications.

A problem that has existed for years and has an extremely negative impact on the running costs for operational PLM deployment is the need to make constant changes to initial customizing for each new basic PLM version. The reason for this is that the API interfaces of the PLM solutions, which for the most part were developed in the 1990s, offered very few customizing options, which have to be updated with every new basic PLM version (□ approx. 20-30% of the original customizing effort). Current software technologies provide automatic solutions for all upgrades via repositories and analyses of differences. In this case, this is also referred to as low-code engines or interactive configuration instead of customizing. In the case of PLM applications in a SaaS cloud, it is important that only configuration is possible. This imposes substantial limitations on operational customization of a PLM solution.

4.4 Traceability, security, transparency

In recent years, a number of technologies have reached maturity, each of which makes its own contribution to ensuring that requirements regarding traceability, security and transparency are met. To date, they have played a subordinate role when it comes to designing in-house PLM architectures. They are, however, increasingly demonstrating their potential in the context of virtualization and cross-enterprise collaboration.
Blockchain technology, familiar from cryptocurrencies, allows sequential data packets in a distributed process

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8 https://blog.turbonomic.com/blog/on-technology/cloud-scalability-scale-vs-scale

to be validated and can thus ensure traceability and security against manipulation.
In general, **distributed ledger** technology eliminates the single point of failure in centralized IT architectures using P2P technologies. They can be used, for example, to map the status and fulfillment of **smart contracts**. Distributed architectures or peer-to-peer (P2P) concepts are a key element in that data management is not the sole responsibility of a single partner or provider and instead is ideally distributed across all the partners in a traceable manner.

Non-fungible tokens (NFTs) are already being used to represent virtual assets. When applied to the product lifecycle, these could be used to represent models or patents, for example.

Digital signatures are used for both encryption and tamper-proof authentication of the sender or author of data, models, documents and other containers.

Digital rights management (DRM) is now widely used in the entertainment industry, among others. The application of DRM concepts to engineering content such as models and data containers, data marketplaces, etc. appears to be a wise move.

In addition to the technologies listed here, there are other components such as **digital watermarking** and **steganography** that enhance digital trust capabilities but are currently being used to a very limited extent in PLM architectures.

4.5 Openness and standardization of data and interfaces

As described above, product lifecycle management comprises a large number of capabilities. But a PLM architecture also comprises numerous individual systems, which only in their entirety and in interaction with each other do they characterize a PLM architecture. This is why openness and standardization take on a special significance within the context of the digitalization of product development processes. The premise that the development processes in complex systems rely on efficient collaboration in partner networks and across individual disciplines is important. This collaboration is a result of the complexity to be addressed and is clearly reflected in the V-model.

In the partner networks, development tasks are performed in IT infrastructures from different system manufacturers. Individualized design tools, simulation programs and development environments that are geared to the task at hand are used. Intermediate results are exchanged between the development partners or made available to downstream departments. This collaboration is performed using interfaces, which are costly to maintain and bring no added value. The number of interfaces increases exponentially as the complexity of the product increases. The most efficient interfaces possible are, however, a prerequisite for efficient product development that is capable of sustaining its competitive edge over the long term.

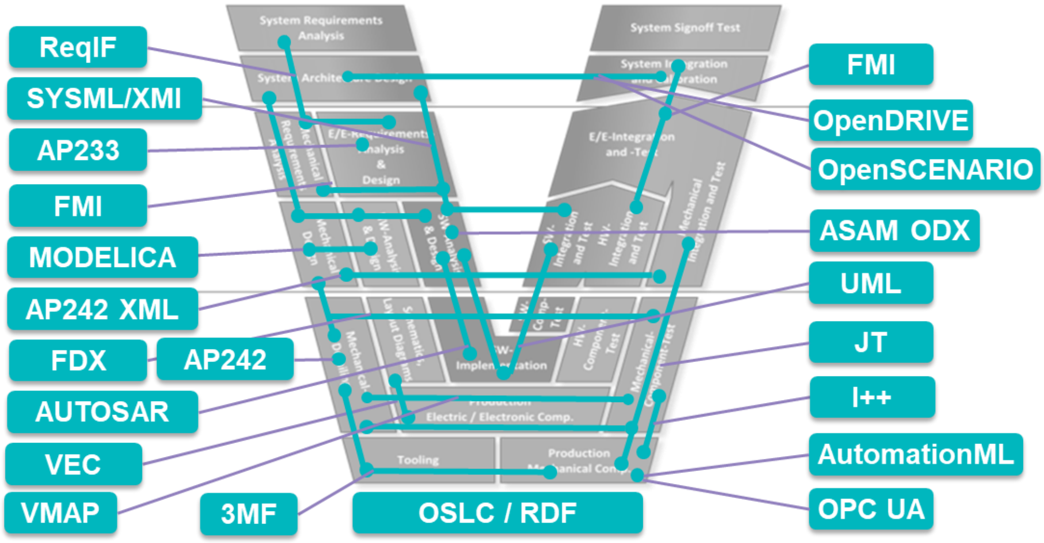

Figure 5: Positioning of standards in the V-model

Open and standardized interfaces make implementation by all market players possible. This means that the time and effort involved in development and maintenance is placed on a broad footing and thus provides maximum investment protection. At the same time, compliance with standards ensures end-to-end digitalization for the respective process step. Openness makes it possible to verify the interfaces and trace the developments that are based on them. It creates trust and makes auditing easier.

From the perspective of the users in cross-enterprise development partnerships, the ability of IT systems to support the exchange of development data using standardized data formats is a key factor for the success of development partnerships. The prostep ivip Association promotes the establishing and use of standards. Figure 5 illustrates the positioning of a selection of standards in the V-model.

5 Approaches for future PLM IT architectures

In the previous sections, the impact of product development on the design of future PLM architectures was discussed, and IT technologies that can be used to improve PLM capabilities when designing and using future PLM architectures were described. The objective is to explore the impact of product development and to develop future-oriented solutions that can support and ensure the competitiveness of a company. The prostep ivip Association took up this challenge back in 2016. In the position paper entitled "Future PLM" [PRO-16], 22 core theses regarding the design of future PLM architectures are formulated and categorized as follows:

- Digital transformation
- Processes and methods
- PLM architectures
- PLM functionality
- PLM implementation
- People and organization

When it comes to future PLM architectures, a transition from monolithic systems to system architectures that can adapt flexibly to changing processes, organizational structures and data structures is being advocated. This modular IT architecture with networked best-of-breed solutions guarantees a flexible working environment that meets users' expectations; the data stored in the domain solutions is not distributed and synchronized across the boundaries of the IT systems but linked instead. These theses are still relevant.

In the following sections, concepts and approaches for future PLM architectures will be introduced, and the impact that the IT technologies described above have on these approaches will be presented.

5.1 Digital thread and digital twin

The digital thread is the common data structure that links physical objects, processes and systems with each other throughout the entire lifecycle. It makes it possible to share information throughout a company with the aim of improving collaboration and reducing errors in decision-making. Digital threads enable companies to quickly access data from every phase of the product development process and provide real-time insights into operation and performance. Figure 6 is a graphical representation of this interrelationship.

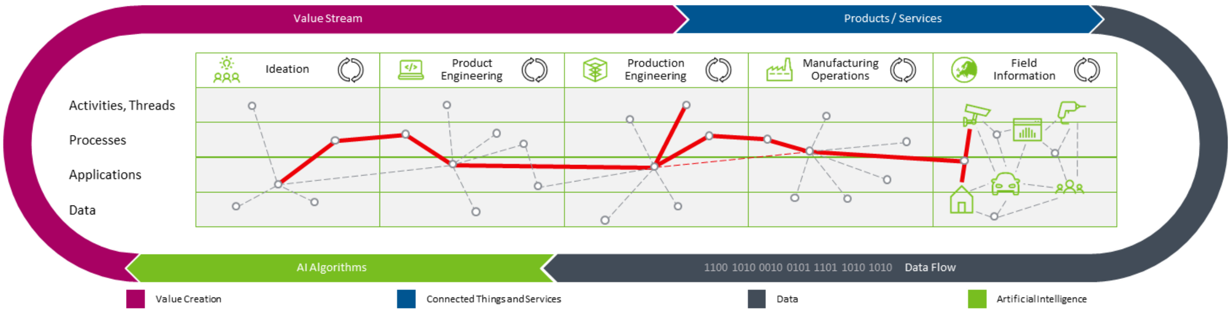

Figure 6: Digital thread throughout the product lifecycle (source: Robert Bosch GmbH)

A much discussed core element in virtual product development is the concept of the digital twin. This concept comprises the comprehensive integration of product models from different development domains, integrated simulations, behavioral models and product-related data. The term "digital twin" was defined around 2002 by Dr. Michael Grieves from the University of Michigan. Grieves defined digital twins in the context of product lifecycle management for the US space agency NASA. The aim was to simulate atmospheres outside the Earth and thus make it possible to build robots that would function reliably under those conditions. The concept illustrated the idea of comparing a digital twin to its engineering design to better understand what was manufactured and what was designed, thus shortening the loop between design and execution. Grieves' conceptual model for the digital twin comprises three main parts: a) the physical product in a real environment (real twin), b) the virtual product in virtual space (digital twin), and c) linked data and information from the virtual and real product.

The many different ways in which term "digital twin" is used in the industrial environments is making it increasingly difficult to achieve a precise interpretation of the term. One thing, however, seems clear. The rise of Industry 4.0 and the Internet of Things (IoT) means that the concept of the virtual twin is being mentioned with ever-greater frequency, and the number of use cases for digital twins is growing. Digital twins are being used to an increasing extent throughout the entire product lifecycle. Traditionally, they are developed during the design and construction phases (with the help of CAD/ CAE models, among other things) in order to create virtual representations of the design and improve products using simulations. Other applications for digital twins involve the maintenance and service of products and systems in the field. Sensors embedded in the physical on-site products and systems collect data. This makes it possible to obtain a more or less complete picture of real-life performance and operating conditions It is also possible to simulate the real environment for the purpose of preventive and predictive maintenance. Just as digital twins can help with maintenance and service, they can also anticipate and improve quality during manufacturing. Digital twins can also include data relating to customer demand and usage data in order to improve adaptability. Incorporating sales data in the digital twin makes it possible to visualize which configurations are being ordered and how configuration-specific revenues compare to the costs involved in creating each configuration. This means that the digital twin can also be used for sales and marketing. A digital twin can, for example, be incorporated in an online configurator or an e-commerce website. Its reach can even extend as far as the human resources department. The digital twin can be used to understand training and certification requirements and ensure that the right people are trained to handle the right product functions.

Today, digital twins primarily serve as data delivery systems or are used for the purpose of validation and error analysis. Up until now, few digital twin concepts take account of available automated value-added services and designing them as autonomous or adaptive systems. The potential for using digital twins in manufacturing industry is sure to increase in the coming years – the basic prerequisite for all applications and services involving digital twins is, however, undoubtedly their quality and the use of resources to create them. The biggest challenges faced when using digital twins in product development are scalability, accuracy and cost. Scalability because digital twins have to process large amounts of data. Accuracy because the models need be accurate if they are to provide reliable predictions. Cost because digital twins require special skills and resources. Digital twins can also be difficult to implement and require an understanding of complex technologies.

5.2 Industrial metaverses

A metaverse is a virtual world or 3D environment where users can interact with each other and explore digital content. It is an immersive, interactive and persistent 3D space where people can explore, collaborate and create something together. Metaverses are widely used for gaming, entertainment, education and business applications. Well-known metaverses include

- Second Life (https://secondlife.com/)
- Sansar (https://www.sansar.com/)
- VRChat (https://hello.vrchat.com/).
- Decentraland (https://decentraland.com/)
- Sandbox.com (https://sandbox.com)

Business applications that use metaverses in the automotive industry include virtual showrooms, virtual tours and virtual dealerships. Industrial metaverses are often seen as data spaces in which digital twins – as virtual representations of physical objects – are created by combining numerous data sources in a single industrial metaverse. These metaverses then allow digital backups to be created using these digital twins. In development, for example, this could be the digital experience of a new vehicle with all the relevant information such as geometry, software functions and even functional data. This information can also be reused in sales – for example, as virtual showrooms that allow customers to explore a virtual vehicle, learn more about its features and configure it to their own particular specifications. Virtual tours make it possible for customers to make a virtual visit to a dealership and learn more about the vehicles without leaving their homes. Virtual dealerships allow customers to buy vehicles directly from the metaverse and have them delivered to their doorstep.

5.3 Enterprise architecture supported by state-of-the-art IT technology

Figure 7 illustrates the support that the IT technologies described above provide in the context of product lifecycle management and which can raise the capabilities that PLM architectures already possess to a new, future-oriented level. This not only gives due consideration to changes in our understanding of data, information and knowledge but also makes it possible to improve the handling of distributed data, information and knowledge and provide easier access to it.

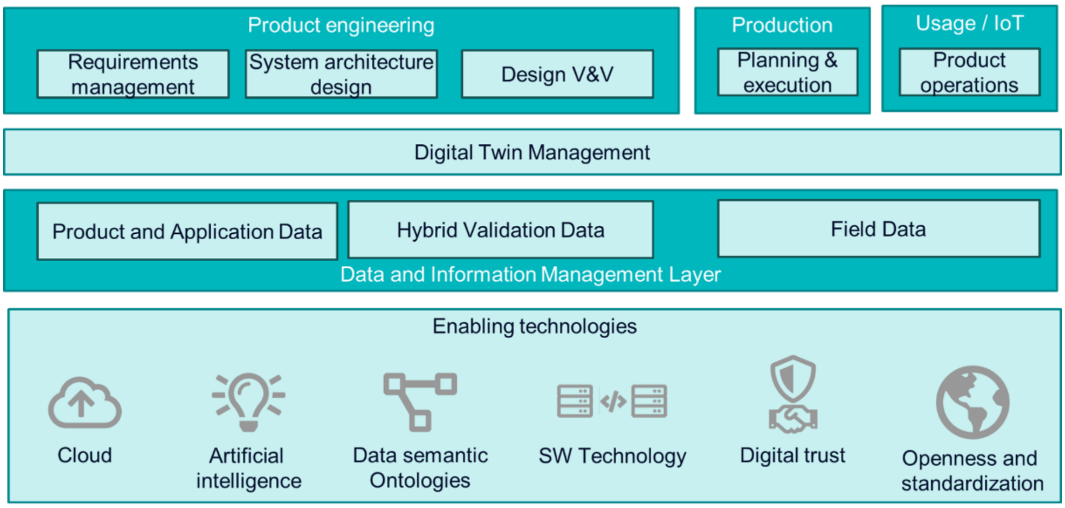

Figure 7: New technologies enhance product lifecycle management capabilities

6 Future PLM architectures in the prostep ivip Association

The prostep ivip Association is committed to developing innovative approaches and standards for product data management and virtual product creation. This understanding also applies to the work performed in the prostep ivip Association's project groups.

The aspects of future PLM architectures addressed in this white paper are not only firmly anchored in the Standardization Strategy Board but also in a number of other ongoing and recently completed project groups and activities carried out by the prostep ivip Association.

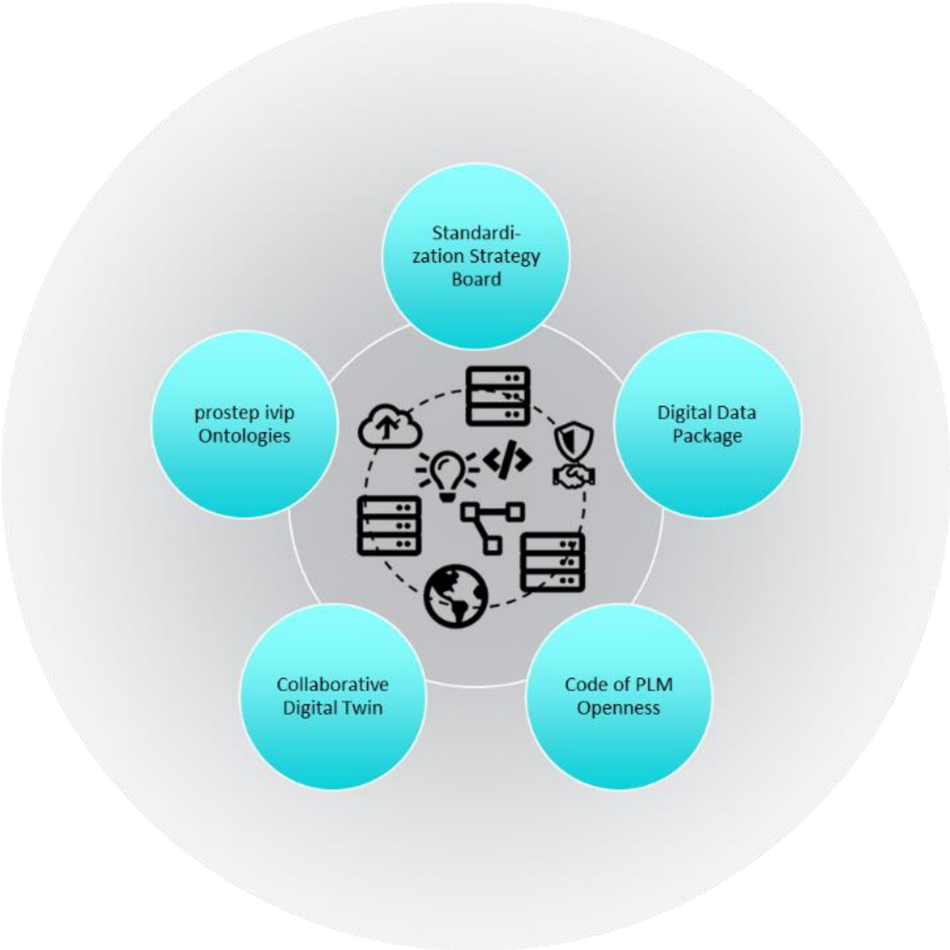

Figure 8: Anchoring of topics relating to PLM architectures in the prostep ivip Association

- The **Integrated Collaboration Framework (ICF)** project group has developed a federated PLM architecture and an ontology to support cross-discipline and cross-enterprise development partnerships.
- The **Digital Data Package (DDP)** project group is developing and describing a data exchange format that can be used to exchange the semantically interrelated and linked development data stored in different IT systems in the PLM architecture between development partners and across company boundaries in the form of digital data packages.
- **Code of PLM Openness (CPO)** is an open initiative of the prostep ivip Association and is sponsored by the German Federal Ministry for Economic Affairs and Energy (BMWK). The specifications draw up by the CPO and the certification measures it has carried out are aimed at establishing openness and thus ensuring the easy integration of IT applications in networked environments (e.g. corporate networks, IoT).
- The objective of the **Collaborative Digital Twin (CDT)** project group is to develop a definition and content for collaborative digital twins from the perspective of the prostep ivip Association and to bundle current activities. This also includes continuation of the ICF/CEEC and psi Ontologies project groups, as well as work on topics such as IT architectures for digital twins, variant and configuration management and human competencies.

- The **Cross-Discipline Lifecycle Collaboration Forum (CDLC Forum)** was set up in 2017 with the aim of improving cross-domain collaboration in engineering environments throughout the entire system lifecycle. CDLC makes use of linked data technologies, which ultimately form the semantic network within the PLM architecture.

A number of different project groups in the prostep ivip Association are thus examining the topic of PLM architectures from their own specific perspective. The work performed in the project groups in the future will continue to focus on PLM architectures.

7 Summary

This white paper shows the impact that product development and new technologies can have on the future design of PLM architectures and which technologies are available for this purpose or can be used to design of PLM architectures.

As far as users are concerned, the boundaries between IT systems will increasingly fade into the background, and they will access physically distributed data and information without having to worry about which system it is actually stored in. They might be synchronously accessing data and information that is physically stored in different systems, but it feels like a unified data set. Overarching semantic networks and, of course, communication between PLM applications make this possible and help users focus to a greater extent on their value-adding engineering activities in product development.

As far as IT system developers and providers are concerned, this means that their IT systems will have to integrate in future PLM architectures. IT systems will always be an integral part of the whole and will only be able to achieve their full potential in virtual product development in interaction with other IT systems. IT systems that have not been sufficiently prepared for communication with other IT systems will, in the future, have a hard time. In light of this fact, providers of IT systems that are open to supporting standards can gain a competitive edge over their market competitors. This applies to both communication standards and standards for mapping data and information, since the ability of an IT system to communicate and integrate is increasingly becoming a system capability that is crucial in terms of the customer's decision to buy.

The development of PLM architectures will, of course, never end and will never reach a point where it could be said that development has been completed and there is no more room for improvement. This is already evident from the fact that the products to be developed are naturally also subject to innovation processes. In the automotive industry, the development of autonomous driving is currently highly dynamic in nature, with the virtual validation of highly automated and autonomous driving functions posing major challenges. Associated with this is the use of artificial intelligence in the products, all the way through to learning vehicles, as well as the flow of information from the products back to development and thus into the PLM architecture, where this information must in turn become part of the PLM data architecture. It can be assumed that this field, among others, still offers great potential for research and development.

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