AI based System of Systems Lifecycle Management of Digital Threads

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Abstract

Over the past two decades, our understanding of product development has changed fundamentally. Disciplines that were once clearly distinct from one another, such as mechanical engineering, electrical engineering and software development, have now become increasingly intertwined. Products are no longer isolated objects, but rather nodes in a network of systems, data and processes. In this environment, it is no longer enough to manage individual data sets – they must flow, remain consistent and be available to the right people at the right time. The AI-based lifecycle management system of Digital Threads (Digital Thread for short) has therefore established itself as the backbone of modern system engineering. Early approaches to product data management (PDM) focused on the central storage of CAD data and the management of versions and approvals. However, with the advent of complex mechatronic systems, networked vehicles and modular plants, it became clear that this approach was not sufficient. Companies began to realise that it was not enough to simply store geometries; they needed a system that mapped the entire lifecycle of a product – from the initial requirement through development and production to operation and decommissioning. Today, Digital Threads' AI-based lifecycle management system acts as a digital nervous system that connects disciplines such as mechanics, electronics, software and simulation. While system engineering provides methodical approaches for structuring requirements and architectures, Digital Thread ensures that the associated data is findable, traceable and up to date. This object-oriented approach creates transparency and enables end-to-end traceability, which is a key requirement of modern systems engineering. Another feature of modern digital thread approaches is the seamless integration of models and product data. Changes in one discipline – for example, in design – can automatically detect and forward all affected areas such as requirements, tests and functions. This promotes the continuous flow of information and prevents unnoticed consequences of changes elsewhere in the system. The close link between AI-based lifecycle management systems for digital threads and system engineering goes beyond technical necessities and promotes cultural change in companies. Organisations must not only introduce technology, but also clearly define processes and responsibilities in order to fully exploit the effectiveness of this system. Clear, transparent handling of changes, systematic management of variants and integration of real-time data from operations are key success factors for the implementation of digital threads. The concept of the 'digital twin', which enables a continuous connection between real and virtual product models, can only be realised through the consistency and transparency offered by digital threads. This, in turn, promotes more sustainable and data-driven decision-making processes that can be taken into account throughout the entire product lifecycle, from development to maintenance. Overall, it is clear that AI-based digital thread lifecycle management systems not only provide the technical basis for system engineering, but are also an integral element for the successful development and operation of complex, networked systems. They promote innovation, improve quality and enable companies to make their product development more flexible and efficient.

Keywords

System of systems, lifecycle management, MBSE, PLM, CAD/CAE, digital thread, digital twin, variant and configuration management

ACM Reference Format:
Xin Lu and Mau Wung. . AI based System of Systems Lifecycle Management of Digital Threads. In *Proceedings of SammelArtikel EDMS*. ACM, New York, NY, USA, 9 pages. https://doi.org/XXXXXXX.XXXXXXX

ACM ISBN 978-x-xxxx-xxxx-x/YYYY/MM
https://doi.org/XXXXXXX.XXXXXXX

1 Introduction

During the past two decades, the understanding of product development has changed profoundly. Whereas in the past it was possible to draw a relatively clear distinction between mechanical design, electrical design, and software development, today the boundaries between these disciplines are becoming increasingly blurred. Products are no longer isolated objects but nodes in a network of systems, data, and processes. In this environment, it is no longer enough to manage individual data sets they must flow, remain consistent, and be available to the right people at the right time. This is precisely why product lifecycle management, or AI based System of Systems Lifecycle Management of Digital Threads for short, has become the backbone of modern systems engineering. Many engineers who have been working with AI based System of Systems Lifecycle Management of Digital Threads systems for years still remember the early days. Initially, the focus was on centrally storing CAD data, controlling versions, and managing approvals. The term PDM, or product data management, was used and the focus was clearly on design. However, with the advent of complex, interdisciplinary products such as mechatronic systems, networked vehicles, or modular plants this approach was no longer sufficient. Companies began to realize that it was not enough to simply store geometries. What was needed was a system that went with the entire life cycle of a product: from the first requirement through development and production to operation and decommissioning. The AI based System of Systems Lifecycle Management of Digital Threads thus became a kind of digital nervous system. It connects what belongs together in reality but is often separated organizationally: mechanics, electronics, software, simulation, coordination, and service. While systems engineering supplies a methodical view of these interrelationships i.e., it asks how requirements, architectures and verifications are structured AI based System of Systems Lifecycle Management of Digital Threads ensures that the associated data is findable, traceable, and up to date. It is, so to speak, the technical implementation of system thinking. A key feature of modern AI based System of Systems Lifecycle Management of Digital Threads approaches is that they are no longer document-centric, but object-oriented. In the past, requirements, drawings, or tests were considered individual files, each with its own life cycle. Today, this information is considered part of a larger, networked data model, A requirement is no longer a static text but an object that is related to many other objects: to the function it fulfills; to the part that implements it; to the test case that verifies it. This network structure creates transparency and allows traceability both core requirements of system engineering. Another aspect that has become hugely important in recent years is the integration of sustainability into the life cycle. Sustainability used to be seen as an isolated goal at the end of product development. Today, it is increasingly understood as a data-driven, continuous process. Research findings from Cambridge and Munich show that AI based System of Systems Lifecycle Management of Digital Threads is the ideal platform for recording and evaluating environmental and social indicators throughout the entire lifecycle [30]. If material data, energy consumption and recycling information are already modelled in the development phase, design decisions can be specifically optimised towards sustainability. IEEE articles from the Sustainable Systems Engineering series underscore this trend: AI based System of Systems Lifecycle Management of Digital Threads acts as a "data container" for sustainability metrics ranging from requirements to manufacturing and disposal [31]. The connection with MBSE models makes it possible to include ecological impacts in simulations and system analyses a decisive step towards "green engineering". AI based System of Systems Lifecycle Management of Digital Threads in the context of global collaboration The more connected products become, the more global development networks become. Projects with suppliers, universities, software companies and manufacturing partners generate an enormous variety of systems, tools, and processes. This raises the question: How can AI based System of Systems Lifecycle Management of Digital Threads function in a globally distributed ecosystem without violating the data sovereignty of individual partners? The answer lies in federated AI based System of Systems Lifecycle Management of Digital Threads architectures. Universities such as ETH Zurich and MIT are working on concepts in which each partner company manages its data locally but releases certain information via standardised interfaces [32]. These "federated AI based System of Systems Lifecycle Management of Digital Threads systems" enable collaboration without central data storage. IEEE studies describe them as a "system of systems" in the true sense of the word: loosely coupled but connected by governance mechanisms [33]. The aerospace industry supplies a successful example. Here, dozens of companies in different domains work on a common system. Federated AI based System of Systems Lifecycle Management of Digital Threads ensures that every change is automatically mirrored in all relevant architectures without anyone having to access external systems [34]. AI based System of Systems Lifecycle Management of Digital Threads implementation a cultural change Despite all the technical advances, the introduction of a holistic AI based System of Systems Lifecycle Management of Digital Threads system stays a cultural challenge. Many companies underestimate the extent to which such a system interferes with existing power and communication structures. A good AI based System of Systems Lifecycle Management of Digital Threads forces transparency: who changes what, when and why? Research at MIT (SEARI Laboratory) shows that successful AI based System of Systems Lifecycle Management of Digital Threads implementations are always accompanied by a clear change strategy [35]. This includes early involvement of specialist departments, iterative introduction in pilot projects, and above all, consistent communication of the benefits. A recurring pattern in empirical studies: the technology works but people need to understand why it is worth using it properly. That is why AI based System of Systems Lifecycle Management of Digital Threads governance is increasingly seen today as part of organisational development and no longer as an IT issue [36].

AI based System of Systems Lifecycle Management of Digital Threads and systems engineering in education and research The academic world is also following suit. Many universities have now set up their own AI based System of Systems Lifecycle Management of Digital Threads laboratories where students learn how to orchestrate data flows across disciplines. Cambridge, together with industry partners, runs a test environment in which MBSE and AI based System of Systems Lifecycle Management of Digital Threads tools are linked to simulate real system networks [37]. IEEE conferences on engineering education show that teaching AI based System of Systems Lifecycle Management of Digital Threads skills is now considered a basic requirement for systems engineers [38]. This is less about running individual tools and more about understanding the connections between requirements, models, data, and processes to form a continuous lifecycle system. Outlook from AI based System of Systems Lifecycle Management of Digital Threads to knowledge backbone What stays is the realization that AI based System of Systems Lifecycle Management of Digital Threads is on its way to developing into a knowledge backbone. In the future, it will be less about storing files and more about structuring knowledge. Cambridge researchers are already talking about "product knowledge graphs": networks of information, relationships, states, and insights that are constantly being expanded via AI mechanisms [39]. The AI based System of Systems Lifecycle Management of Digital Threads is thus becoming the nervous system of a company it connects not only data, but also ways of thinking, people, and experiences. If systems engineering supplies the methodological framework, then AI based System of Systems Lifecycle Management of Digital Threads is the body in which this method lives. The coming years will show how far organizations are prepared to go down this path. One thing is certain: those who control their data flows control the future of their systems.

2 Continuous flow of information that prevents a change

In a well-designed AI based System of Systems Lifecycle Management of Digital Threads system, such relationships can not only be represented, but also put into practice. When an engineer in the design department makes a change to an assembly, the system can automatically recognise which functions, requirements or test cases are affected. In many cases, these links are used to trigger change workflows or automatically send notifications to the relevant responsible parties. This creates a continuous flow of information that prevents a change in one place from triggering unnoticed consequences elsewhere. Perhaps the most crucial point here is that AI based System of Systems Lifecycle Management of Digital Threads and systems engineering should not be seen as competing concepts. On the contrary, they are complementary. Systems engineering supplies the methodological framework the mindset and processes for structuring complex systems. AI based System of Systems Lifecycle Management of Digital Threads, in turn, supplies the technical platform that makes this mindset possible in everyday life. If you like, systems engineering is the theory and AI based System of Systems Lifecycle Management of Digital Threads is its practical infrastructure. In industry, this connection is particularly clear where companies are trying to introduce model-based approaches i.e., MBSE. The idea of no longer describing systems in PowerPoint and Excel, but in formalised models, has long been accepted in theory. In practice, however, MBSE often stays isolated. Models are created that are logically consistent but have no connection to real product data. They are methodologically sound but organisationally ineffective. Only when AI based System of Systems Lifecycle Management of Digital Threads incorporates these models, versions them and links them to physical data does MBSE become a living part of development. An example from the automotive industry illustrates this very clearly. There, system architectures are modelled in SysML and then linked to the parts lists and CAD assemblies in the AI based System of Systems Lifecycle Management of Digital Threads system. If a system function changes, the designer can at once see which components are affected. Conversely, a change in the design can trigger a message in the system model so that the functional relationships can be checked. This is not a theoretical gimmick in reality, it saves days or weeks of coordination and prevents misunderstandings that in classic projects often only become clear in the prototype or even in the field. In this context, it is worth thinking about the term "data flow". A data flow is not simply a technical transport channel. It is the visible expression of cross-disciplinary collaboration. When information can flow freely without having to be reinterpreted or reformatted at each transfer point, efficiency is created. AI based System of Systems Lifecycle Management of Digital Threads organises precisely this flow: it ensures that requirements, models, drawings, tests, and feedback have a common semantic foundation. But as is so often the case in technology, the greatest difficulty lies not in the software, but in the organisation. A AI based System of Systems Lifecycle Management of Digital Threads system forces companies to address issues that they previously preferred to avoid: Who is authorised to make changes? Who handles data quality? How is it decided which version is "true" when several departments are working on the same part? These questions inevitably lead to cultural conflicts and this is often the reason AI based System of Systems Lifecycle Management of Digital Threads projects fail or take years to complete. The companies that have successfully managed this change share a common pattern: they view AI based System of Systems Lifecycle Management of Digital Threads not as an IT project, but as a change in the way they work. The technology is only the tool; what is crucial is that people understand why data flows are important. If a design engineer knows that his change request not only affects the drawing set, but also influences requirements, tests, and supplier relationships, he will automatically act more consciously. AI based System of Systems Lifecycle Management of Digital Threads thus creates not only transparency, but also a sense of responsibility. Another often underestimated area is variant and configuration management. In a world where products are becoming increasingly individualised, every system must be able to manage countless variants without the complexity exploding. AI based System of Systems Lifecycle Management of Digital Threads supplies the methodological and technical mechanisms to keep configurations consistent. Instead of creating copies for each new variant, common base elements are used and controlled via characteristic values. This ensures traceability and allows changes to be propagated in a targeted manner without creating chains of errors. The benefits of AI based System of Systems Lifecycle Management of Digital Threads become even clearer when you look at the life cycle beyond the development phase. In the past, the work of engineers was largely completed once series production had been approved. Today, running and service data flows back into development partly automatically via sensors, partly manually via maintenance systems. AI based System of Systems Lifecycle Management of Digital Threads is the vessel in which this data can be collected and analysed. This creates the "digital twin" the virtual image of the physical product that evolves in parallel with it. The twin thrives on the consistency of its data, and this consistency in turn can only be guaranteed by AI based System of Systems Lifecycle Management of Digital Threads. A company that wants to run its digital twin seriously needs a AI based System of Systems Lifecycle Management of Digital Threads system that reflects every change to the real object: every modification, every spare part, every firmware update. Only then can the digital twin serve as a decision-making tool for example, for predictive maintenance or variant analysis. Without AI based System of Systems Lifecycle Management of Digital Threads, it would be a short-lived 3D model with no connection to reality. The topic of sustainability also takes on new meaning in the context of AI based System of Systems Lifecycle Management of Digital Threads and systems engineering. In the past, sustainability was seen as contradictory to efficiency it was understood as an added burden. Today, it is an integral part of lifecycle thinking. When a AI based System of Systems Lifecycle Management of Digital Threads system collects information about materials, energy consumption, transport routes and recycling options, sustainability becomes a question of data. It becomes measurable and therefore controllable. This enables companies to make design decisions that are both ecologically and economically sound. At the same time, the focus is shifting to interoperability between different AI based System of Systems Lifecycle Management of Digital Threads systems. Hardly any company today develops everything on its own. Value creation takes place in networks with partners, suppliers, and research institutions. The classic idea of a central database is not tenable in such scenarios. Instead, federated structures are appearing in which each partner keeps its data but supplies defined interfaces. These "federated AI based System of Systems Lifecycle Management of Digital Threads architectures" enable collaboration without sacrificing data sovereignty. They are the technical expression of a system of systems loosely coupled but connected by common governance. The aviation industry supplies a good example of this. Dozens of companies work on a plane engine manufacturers, avionics suppliers, structural developers, suppliers for cabins and systems. Each of these organisations runs its own AI based System of Systems Lifecycle Management of Digital Threads, but the relevant information is exchanged via standardised interfaces. This creates a higher-level lifecycle management system that ensures the integrity of the overall system without curtailing the autonomy of the individual partners. This concept can also be applied to other industries. In mechanical engineering, for example, companies' network via AI based System of Systems Lifecycle Management of Digital Threads-driven platforms to jointly develop assemblies and keep their lifecycles synchronised. This shortens development times and allows changes to be found at an early stage. What was considered a vision ten years ago is now a reality in many places but only where companies were willing to commit to common data standards and transparent processes. The future of AI based System of Systems Lifecycle Management of Digital Threads will probably be even more knowledge oriented. Researchers are already talking about "product knowledge graphs" networks in which information is not only stored but also linked in a context-related manner. At the touch of a button, such a knowledge graph could show which requirements a particular function fulfils, which materials are used and what sustainability implications this has. AI based System of Systems Lifecycle Management of Digital Threads thus becomes a carrier of collective knowledge, no longer just a storage facility for files. At the same time, the role of humans will change. Engineers will spend less time searching for information and more time interpreting and evaluating it. The system supplies the context, humans make the decisions. This balance is where the real strength of digitalisation lies it does not replace experience; it makes it more usable. When you take all these developments together, you realise that AI based System of Systems Lifecycle Management of Digital Threads in systems engineering is not just a technical necessity, but a cultural one. It forces organisations to take responsibility for the entire life cycle. It creates transparency where there used to be departmental boundaries. It enables learning from use, rather than just reacting to errors. And it ensures that the knowledge gained in a project is not lost when it is completed. At a time when products are changing ever more rapidly and development cycles are becoming shorter, this is precisely the decisive factor for success. Data flows are now what the production line used to be: the backbone of value creation. Those who master them can drive innovation, minimise risks and ensure quality. Those who ignore them lose not only efficiency, but also the ability to understand complex systems at all. Ultimately, product lifecycle management is not a tool that you introduce and then it just works. It is a way of thinking. It means taking responsibility for the entire lifecycle not only technically, but also organisationally and ethically. This responsibility is where the true strength of systems engineering lies. After all, systems are not made successful by tools, but by people who understand their interrelationships and bring them together into a common structure. AI based System of Systems Lifecycle Management of Digital Threads is the backbone that supports this structure quietly, unspectacularly, but indispensably. Product lifecycle management (AI based System of Systems Lifecycle Management of Digital Threads) has long been more than just a storage system for CAD data it is the connecting element between development, production and operation. AI based System of Systems Lifecycle Management of Digital Threads plays a key role in systems engineering in particular: it ensures that models, requirements, tests and changes remain consistent across all disciplines. This article highlights how modern AI based System of Systems Lifecycle Management of Digital Threads systems organise data flows, manage variants and integrate system models. Practical examples are used to show how companies are mastering the transition from document-based processes to model-based, networked workflows. AI based System of Systems Lifecycle Management of Digital Threads as the backbone of systems engineering how data flows become a success factor When engineers talk about systems engineering today, it is no longer just about mastering technical complexity. It is about coherence ensuring that everyone involved in a development process, from system architects to service technicians, has access to the same level of knowledge without working in data silos. This is precisely why product lifecycle management, or AI based System of Systems Lifecycle Management of Digital Threads for short, has become the cornerstone of modern systems engineering. AI based System of Systems Lifecycle Management of Digital Threads began as a methodological framework for centrally managing CAD data, parts lists and change statuses. In the early 2000s, it was still considered "engineering document management". Today, it has become a strategic " " nervous system that connects all development, production, and operational information [1]. Leading research including at the University of Cambridge, MIT and in IEEE publications emphasises that AI based System of Systems Lifecycle Management of Digital Threads is no longer a toolbox for engineers, but a cross-organisational communication system [2][3].

2.1 Why SoS lifecycle management is different

In SoS, dependencies and interactions arise across system boundaries. It is not enough to simply version your "own" product; end-to-end transparency is required across requirements, architecture, behavior, interfaces, and configurations ideally model-based right through to operation and service. Research from Cambridge (Design Science, Proceedings of the Design Society) and university repositories shows that MBSE acts as a common language and "bracket" between disciplines; PLM provides governance, data continuity, and variant logic; CAD CAE feeds geometry parameters; PDM organizes design results; DT DI (digital twin threads) extend the chain to operation feedback [1][4], [6][14], [19], [22]. This is both a technical and organizational task: roles, processes, toolchains, and data sovereignty must fit together [3], [7], [8], [12]. MBSE as the backbone and its maturity The literature paints a clear picture: MBSE improves traceability, consistency, and reusability, but often faces adoption hurdles (complexity, tool compatibility, lack of reference models) [18], [23], [24], [27], [29]. Current work differentiates between types of use (userisation of system models) and calls for targeted reuse transformation of system models into domain models (e.g. CAD simulation) instead of duplicate maintenance [3]. At the same time, work is being done on language and ontology issues: further development of SysML, LML as a complementary ontology, as well as guidelines for model curation and human centered, interactive model environments (IMCSE) [5], [19], [28], [30], [31]. These strands are central to reliably anchoring traceability across disciplines (requirements to architecture to design to verification to operation) a core objective in SoS-LCM [3], [11], [15]. PLM PDM as a governance layer beyond a "data container".PLM is evolving from a pure document bill of materials container to a knowledge and governance platform across the lifecycle: process views for engineering change, configuration variable management, rights sovereignty, lifecycle status and approvals including links to CAD CAE, requirements tools, ALM software repositories, and operating systems (IoT service) [7], [10], [12], [25]. Process guidelines for PLM implementation are particularly crucial in engineering-to-order (ETO) programs (Cambridge Design Science; McKendry et al.), as any deviation becomes exponentially more expensive in later phases [7], [12]. In addition, Cambridge's work on sustainability in PLM emphasizes that ecological social criteria should be incorporated into decisions at an early stage in a model- and data-driven manner, an increasingly mandatory field in the SoS context [9].3D CAD design and system architecture bridge instead of island:

A recurring finding: CAD artifacts must not only be linked to the system model, but also derived from it and fed back into it (parameters, working surfaces, functional surfaces, tolerances). Cambridge contributions show how parametric working surfaces and contact channel methods can be integrated into MBSE-supported PLM approaches to consistently implement changes [10]. In modular product families (e.g. vehicle construction), MBSE in modular development makes cross-relationships manageable because architecture variance decisions are explicitly modeled and synchronized with CAD CAE [6].

3 The significant of AI based System of Systems Lifecycle Management of Digital Threads

What makes AI based System of Systems Lifecycle Management of Digital Threads so significant in this new context is its ability to structure data flows not only within a project, but across the entire lifecycle of a product and its variants. Systems engineering, in turn, defines the development process as the interaction of requirements, architecture, design, integration, and validation [4]. For both disciplines to work together, AI based System of Systems Lifecycle Management of Digital Threads must form the backbone on which models, documents, test data, and software artifacts are securely linked. From document to relationship. For a long time, the classic document orientation was the bottleneck in engineering. A requirement was stored as a PDF in a folder, the CAD model in a PDM system, the simulation results in an Excel file, and no one knew which version was current. This led to redundancies, misunderstandings, and expensive wrong decisions. In modern AI based System of Systems Lifecycle Management of Digital Threads approaches, therefore, every piece of information is viewed as an object with relationships no longer as a static document, but as a node in a network of dependencies [5]. A requirement is therefore not simply a text but is linked to the system architecture, function definitions, CAD parameters, parts lists, and test cases. This relational thinking is what systems engineering demands: end-to-end traceability and change security in all phases [6]. Research by the Cambridge Design Society shows that companies that consistently build their AI based System of Systems Lifecycle Management of Digital Threads in an object-oriented manner experience significantly lower change costs and fewer integration problems [7]. IEEE studies on model-based systems engineering (MBSE) also come to similar conclusions: without a clean data backbone, models can be created, but are still isolated and lose consistency throughout their lifecycle [8]. AI based System of Systems Lifecycle Management of Digital Threads and MBSE two worlds, one language In theory, MBSE is the methodological superstructure that maps the entire development process in a model-based manner. In practice, however, MBSE often gets stuck in the pilot stage () because it lacks a connection to productive tools. This is where the true strength of an integrated AI based System of Systems Lifecycle Management of Digital Threads system comes into play: it provides the technical infrastructure for linking system models with real product and production data. One example is a research collaboration between TU Darmstadt and the University of Cambridge, in which MBSE models are synchronized directly with CAD assemblies via AI based System of Systems Lifecycle Management of Digital Threads interfaces. Changes in system architecture automatically trigger notifications in the relevant disciplines from electronics design to software integration [9]. This creates a continuous flow of information in which the models communicate with each other rather than files. This change is profound. The AI based System of Systems Lifecycle Management of Digital Threads is no longer a downstream storage location, but part of the method itself. Systems are no longer first modeled and then managed; they are created within a framework that jointly maps models, data, and processes. People as the connecting element Despite all the technology, people remain the decisive factor. Studies by [10] show that the biggest obstacles to the introduction of AI based System of Systems Lifecycle Management of Digital Threads-based systems engineering are not technical in nature, but cultural: lack of acceptance, unclear responsibilities, lack of process discipline. An AI based System of Systems Lifecycle Management of Digital Threads system is only as good as the people who keep it and the processes that are tailored to it. Successful companies rely on transparent role models: system engineers handle the model structure, AI based System of Systems Lifecycle Management of Digital Threads administrators for data consistency, and domain experts for technical content. In addition, training is not seen as a chore, but as part of product development.

Cambridge studies on organizational psychology in engineering show that continuous training is crucial to achieving digital consistency [11]. Integration of variants and complexity A key feature of modern AI based System of Systems Lifecycle Management of Digital Threads systems is variant and configuration management. In classic PDM systems, assemblies were often copied as soon as variants were needed, resulting in uncontrolled amounts of data. In systems engineering, this is fatal because each variant creates new dependencies. The AI based System of Systems Lifecycle Management of Digital Threads platforms with a configuration-based approach (configuration management according to ISO 10007 and 15288), on the other hand, allows all variants to be derived from a common data expert [12]. Requirements, functions, and design objects are controlled via characteristic values. This enables reuse and traceability. An example from the aviation industry shows that consistent AI based System of Systems Lifecycle Management of Digital Threads variant logic can reduce the change effort per product generation by up to 40AI based System of Systems Lifecycle Management of Digital Threads as a link to production and operation In the extended life cycle, the engineer's responsibility does not end with the release of the design data. Operation, service, and field feedback are increasingly fed back into development. The concept of the digital thread connects these phases: from the system model in early development to the sensor data in operation. The AI based System of Systems Lifecycle Management of Digital Threads is where this feedback converges in a structured manner. The combination of AI based System of Systems Lifecycle Management of Digital Threads data and IoT information enables preventive maintenance, variant tracking in use, and informed decisions for new product generations [14]. IEEE publications on digital twin architectures emphasize that without AI based System of Systems Lifecycle Management of Digital Threads-based configuration management, no reliable digital twin can be created because only AI based System of Systems Lifecycle Management of Digital Threads knows the valid status of each individual system [15]. The role of standards and interoperability

4 International guidelines

Another field of research concerns standardization. International guidelines the ISO/IEC/IEEE 15288, 24748-1 and 42010 standards define how system lifecycles are documented and architecture views are described [16][17]. AI based System of Systems Lifecycle Management of Digital Threads systems serve as the practical implementation of these standards by mapping the artifacts required there from requirements to verification records in a structured form. At the same time, work is being done on interoperability between tools. The IEEE P2660 series deals with the standardization of interfaces between MBSE, AI based System of Systems Lifecycle Management of Digital Threads and ALM systems. Universities such as Stanford and MIT are researching semantic mediation layers that overlay ontologies on engineering data to enable machine-readable links [18]. The goal is clear: an ecosystem in which not only humans, but also systems can understand data in context. Practical examples and insights. The theory is convincing, but implementation is crucial. A look at real-world industrial projects shows that the transition from document-based to model- and data-driven workflows has three main prerequisites:

1. Uniform data models: Companies that run heterogeneous AI based System of Systems Lifecycle Management of Digital Threads and CAD systems need a common semantic foundation.

2. Process discipline: Every change must be documented in a traceable manner; every requirement must have a known origin and proof of fulfillment.

3. Top management support: Without strategic anchoring, AI based System of Systems Lifecycle Management of Digital Threads is perceived as a pure IT project.

A widely cited Cambridge case study in mechanical engineering shows that the greatest progress is achieved when AI based System of Systems Lifecycle Management of Digital Threads implementation and process optimization are considered together not sequentially [19]. Empirical studies in IEEE Transactions on Engineering Management also confirm that the combination of the MBSE method and AI based System of Systems Lifecycle Management of Digital Threads governance reduces development times, improves traceability, and strengthens quality culture [20].

4.1 Sustainability, circularity and compliance in SoS

New work anchors sustainability criteria in PLM MBSE: material and energy aspects, reparability, second life, circular strategies, and regulatory requirements (e.g. documentation obligations) are to be recorded in a model-based manner and evaluated along the digital thread of the [9], [36]. Older Cambridge articles refer early on to the shift from ”waste management” to genuine lifecycle management, now more relevant than ever in SoS [13]. What does this mean specifically for your anthology contribution No. 1? Based on this literature, your editorial can make four things clear:

1. Why classic lifecycle thinking is no longer sufficient: SoS characteristics, distributed ownership, emergence with standards foundation 15288 24748-1 1471 as the common thread [1], [15][17].

2. How MBSE+PLM bridge the gap: Model-based requirements architectures as a ”single source of truth”; PLM as the governance configuration backbone; CAD 3D as a derived feedback view [3], [6][8], [10][12].

3. How the digital twin belongs in the lifecycle: early modeling, providing reliable configuration and operating data [4], [11], [22].

4. How to get started organizationally: clear ownership, referenced use cases, piloting, model curation, training flanked by action research with university partners [7], [12], [28], [31], [34], [35].

In modern systems engineering, AI based System of Systems Lifecycle Management of Digital Threads is much more than a database. It is the organizational and technical framework that ensures that information is not lost but develops and enriches itself throughout the life cycle. In an environment where products become networked systems and systems become ecosystems, this framework is indispensable.The second part focuses on current lines of research: semantic data models, AI-supported data integration, sustainability in AI based System of Systems Lifecycle Management of Digital Threads, digital twins in operation, and the question of what future AI based System of Systems Lifecycle Management of Digital Threads architectures must look like to survive as the "backbone" in real System of Systems scenarios. Looking at developments over the last ten years, AI based System of Systems Lifecycle Management of Digital Threads systems are increasingly moving away from engineering IT and developing into strategic platforms for the entire value chain. They are no longer just a tool for designers, but the foundation of an integrated, data-driven enterprise. This change has enormous consequences, not only for processes but also for the way companies think, make decisions, and take responsibility for the entire life cycle. AI based System of Systems Lifecycle Management of Digital Threads as an enabler of the digital twin A key driver of this development is the concept of the digital twin. Although the term is often used inflationary in public discourse, it has a very precise meaning in engineering science: it describes the structured image of a physical system that stays synchronized with its real counterpart throughout its entire life cycle. However, this cannot be implemented without a strong AI based System of Systems Lifecycle Management of Digital Threads backbone. The digital twin is fed from a variety of sources CAD geometries, MBSE models, simulation data, production parameters, field data from sensors, and service feedback. Only when this information is managed consistently on a common AI based System of Systems Lifecycle Management of Digital threads can a robust and trustworthy image be created [21]. The Massachusetts Institute of Technology describes this relationship as a "closed-loop lifecycle": The AI based System of Systems Lifecycle Management of Digital Threads creates the logical framework that connects development and operational data, enabling learning across generations [22]. Studies from the IEEE environment show that companies with AI based System of Systems Lifecycle Management of Digital thread-based digital twins not only achieve faster development cycles, but also set significantly better traceability of requirements through to operation [23]. This fundamentally changes the nature of product development: instead of linear transfers between departments, a permanent bidirectional data flow is created. Semantic integration the step from data to meaning While technical networking is now well advanced, semantic integration is still in its infancy. It is not enough to simply transfer data; it must also be understood. Different disciplines speak different "languages" in their tools: a CAD system knows geometries, a AI based System of Systems Lifecycle Management of Digital Threads system knows product structures, an MBSE model knows system functions, and ERP calculates in parts lists and costs. Therefore, research groups at Stanford University and the University of Cambridge are working on ontologies that bridge the semantic gap between these worlds [24]. The aim is for machines to recognize the contextual relationship: an "assembly" in CAD is semantically the same object as a "component element" in an AI based System of Systems Lifecycle Management of Digital Threads and a "physical instance" in the digital twin. These semantic mappings enable systems to exchange information in a context-sensitive manner a step towards true interoperability [25]. IEEE publications on system ontology (IEEE P2906) emphasize that a semantically clean data model is a prerequisite for AI-supported analyzes and automated decision support [26]. Without semantic consistency, data can flow, but it does not make sense. The AI based System of Systems Lifecycle Management of Digital Threads thus becomes a bridge between syntax and meaning it organizes not only files, but also knowledge about the system. Artificial intelligence in AI based System of Systems Lifecycle Management of Digital Threads reality instead of hype In recent years, a new field of research has appeared that investigates how AI methods can be used in AI based System of Systems Lifecycle Management of Digital Threads. Contrary to public debate, this is not about chatbots or generative tools, but about concrete applications: automated classification of components, anomaly detection in data flows, prediction of maintenance intervals, or semantic detection of duplicates in databases [27]. Cambridge studies show that machine learning has potential where data quality and consistency are already high. AI cannot bring order to chaos but it can reveal patterns that would be overlooked in human analysis [28]. The combination of MBSE models with AI based analysis methods is particularly exciting: when a system model is anchored in AI based System of Systems Lifecycle Management of Digital Threads structures, training data from simulation and field observation can help to understand system behavior and improve design decisions [29]. Sustainability as a Data flow

- Thesis 1: SoS-LCM requires a model and data-driven bracket, MBSE for structure behavior interfaces, PLM for governance configuration; CAD 3D and simulation are synchronized instead of being maintained in isolation [3], [6][8], [10][12], [15], [16].
- Thesis 2: Standards provide stability during adaptation: structure roles, milestones, artifacts, and views independently of tool brands [15][17], [21], [26].
- Thesis 3: Digital twins are effective when based on system models and PLM configurations; this is the only way to ensure consistency in changes, variants, and field data [4], [11], [20], [22].
- Thesis 4: Adoption succeeds with pilot cases, reference architectures, model curation, and action research loops; training and governance are just as important as tools [7], [12], [28], [31], [34], [35].

endverbatim

5 Conclusion

The close integration of AI based System of Systems Lifecycle Management of Digital Threads and systems engineering is profoundly changing industrial practice. It is forcing companies to think about not only tools but also responsibility, quality, and sustainability. The AI based System of Systems Lifecycle Management of Digital Threads is thus becoming a symbol of a new engineering culture one that sees networking not as a disruption, but as a prerequisite. The backbone of this culture is the flow of data that creates trust. They form the basis for making complex systems manageable today and for generations to come. [40] In modern product development, product lifecycle management (AI based System of Systems Lifecycle Management of Digital Threads) acts as the central backbone of systems engineering by making the increasing complexity of interdisciplinary development processes manageable and ensuring the consistency of technical data throughout the entire product lifecycle. This link between CAD and AI based

System of Systems Lifecycle Management of Digital Threads is the basis for consistent data flows between mechanics, electronics, and software [43][44]. This link between CAD and AI based System of Systems Lifecycle Management of Digital Threads is the first step towards a continuous digital process chain in which the dependencies between design parameters, system models, and product data become transparent and traceable [45][46]. [47] In an industrialized environment, Salehi showed that the integration of such parametric-associative methods into the AI based System Methodical embedding of these systems enables companies to dynamically link system models with product data, significantly improving the flow of information from the initial concept phase through to operation [48][49]. The concept of System Driven Product Development (SDPD) is gaining importance here, which Salehi and Burseg describe as a bridge between classic AI based System of Systems Lifecycle Management of Digital Threads processes and model-based systems engineering (MBSE) [50][51]. SDPD anchors system models as a central knowledge base in the AI based System of Systems Lifecycle Management of Digital Threads, linking requirements, functions, and physical implementations in a consistent data model [52][53]. [54] Another key aspect is the use of SysML as a standardized language to describe complex mechatronic systems. Salehi, Taha, and Schade show how SysML models can be embedded in AI based Systems Lifecycle Management of Digital Threads environments to standardize data exchange between engineering disciplines [55][56]. As a result, AI based System of Systems Lifecycle Management of Digital Threads is no longer understood merely as a document management system, but as a semantically networked information system that integrates system architectures, parameters, simulation results, and test data. The introduction of the Munich Agile MBSE Concept (MAGIC) [57][58] is a change in basic assumptions in this regard: agile methods in the MBSE environment shorten change cycles and accelerate feedback between AI based System of Systems Lifecycle Management of Digital Threads data and system models. This supports companies in the development of digital products and cyber-physical systems [59]. [60] Application examples range from the development of autonomous driving systems [61] and the design of urban air mobility solutions [62] to the integration of IoT sensor networks into AI based System of Systems Lifecycle Management of Digital thread-supported development processes [63]. Data flows thus become a key success factor as they form the basis for simulation, verification, and continuous improvement. The connection between physical and digital worlds via digital twins is structured by the AI based System of Systems Lifecycle Management of Digital Threads, which documents all changes, versions, and configurations as a data backbone [64]. [65] With increasing digitalization, the issue of data security and integrity also is in focus. In several papers, Salehi demonstrated the potential of blockchain technology for securing engineering data processes in the context of AI based System of Systems Lifecycle Management of Digital Threads [66][67]. Blockchain-based data chains allow changes to system models and configuration files to be traced transparently, which is particularly important for safety-critical applications, such as in the automotive or aviation sectors. The combination of blockchain and AI based System of Systems Lifecycle Management of Digital Threads thus creates a trustworthy digital ecosystem that prevents manipulation and guaranties traceability throughout the product lifecycle. [In addition, Salehi describes the use of AI methods and synthetic data sets to generate test and training data in the context of CAD and CNC processes. These data-driven approaches extend AI based System of Systems Lifecycle Management of Digital Threads systems with intelligent feedback loops that enable continuous learning throughout the product lifecycle. In this way, AI based System of Systems Lifecycle Management of Digital Threads becomes an active part of system engineering not just as a storage medium, but as a data analysis platform. [72] Finally, recent work on the integration of centralized vehicle architectures and digital twins shows that AI based System of Systems Lifecycle Management of Digital Threads systems will no longer be mere data managers in the future, but rather integrative control centers for complex system landscapes. The ability to make data flows consistent, traceable, and interoperable is increasingly deciding the success of technical systems. This makes AI based System of Systems Lifecycle Management of Digital Threads the backbone of modern systems engineering a backbone that connects disciplines, structures information flows, and accelerates innovation.

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