A Digital Twin Platform-based Approach to Product Lifecycle Management: Towards a Transformer 4.0

Henrique Silva[1,2], Tomás Moreno[1,2], António Almeida[1,2], António Lucas Soares[1,2] and Américo Azevedo[1,2]

[1] INESC TEC, Rua Dr. Roberto Frias, 4200-465, Portugal
[2] Faculty of Engineering, University of Porto, Rua Dr Roberto Frias 378, 4200-465, Portugal

Abstract. Recently, we have been observing a significant evolution in products, machines, and manufacturing processes, towards a more digital and interoperable reality. In this sense, the power transformers sector has also been evolving to develop smart transformers for the future, capable of providing the digital capabilities to leverage new services and features that follow its entire life cycle, from the design and manufacturing to the use and dismantling/ recycling. In this sense, this paper aims to present and demonstrate how an innovative digital twin platform can be used in a secure and trustable way for the enhancement of the power transformers' performance and potential lifespan, enabling, at the same time, the promotion of new business models. A real use case is also presented to demonstrate the importance of Asset Administration Shells (AAS) for power transformer life cycle management, as well as the use of the International Data Spaces (IDS) for the secure and trustable horizontal interoperability along with the different actors of the value chain, from the manufacturers to the power network and maintenance services companies.

Keywords: Smart Transformers, Asset Administration Shell, Digital Twin, Product lifecycle.

1 Introduction

Industry 4.0 is designated as the fourth industrial revolution and is often associated with smart manufacturing [1] and is supported by innovative digital technologies such as the Industrial Internet of Things, Cyber-Physical Systems, Big Data, and other future-oriented technologies. [2]. Such types of technologies lead to the integration, automation, and optimization of manufacturing processes [3, 4]. This revolutionary context of integrated industry [1] enabled the concept of the Digital Twin (DT) as a means to connect the physical power transformers (PT) in the manufacturing shopfloor with the digital space [5, 6] and its capabilities, therefore enabling digital data-driven services.

As methods of energy generation and distribution change, transformer design and manufacturing must adapt to meet evolving global standards, reduce coil losses and improve transformer performance. Transformer design today is affected by several changing conditions in our electricity distribution networks. Energy generation, for example, is increasingly being achieved by renewable sources like wind and solar power, replacing more traditional forms of energy generated through power plants. Applications such as electric mobility are gaining popularity, meaning increased pressure on the transmission and distribution network.

The influence of the digital in this sector is also growing as seen in smart grid development, in the impact of complex monitoring and automated processes enabled by the increasing prevalence of cyber-physical systems, and last, but not least, the importance of global energy efficiency regulations.

The development and production of power transformers as is done today, is no longer compatible with this ‘Energy 4.0’ trend, due to a series of reasons:

- Technical information flow is not sufficiently open, shared, and efficient, e.g., in an internet of things era where all information is potentially shared, product and process design information or testing data still predominantly follows in a unidirectional and sequential flow from the project to the suppliers, customers, shopfloor and other stakeholders;
- Relevant information from product operation and usage during the lifecycle remains low, limiting not only the failure mode and effects and root cause analysis but also the continuous product improvement through an expansion of the design knowledge base;
- Designers and other stakeholders which make the creative workforce behind a product/service are often stuck on repetitive tasks, that, while crucial to its development, add little to no value to the final product, and as such industry is not making the most of its talent basis and failing to implement true open innovation practices.

Driven by the development of new digital concepts, power transformers have noteworthy opportunities, creating new affordances, through innovative data-enabled functions, leading to more competitive products for a fast-evolving sector that strongly impacts our quality of life and economic competitiveness. The proposed concepts presented in this paper, grounded into the digital era of the DT, can be separated into three different pilar subjects of study: knowledge-based engineering, lifecycle management, and product-service systems. The presented paper follows a real case study of a Portuguese power transformer manufacturer that aims to create a DT Platform that can support and improve the PTs' performance of their clients.

2 Literature Review

2.1 Digital Twin

The DT can be perceived as an opportunity to optimize the performance of a manufacturing process. In the Industry 4.0 context, manufacturing is evolving from knowledge-based manufacturing to smart manufacturing, in which "smart" refers to the use of data-driven technologies [7]. On these service-oriented technologies, data and information can be perceived as the common ground and the key element [8]. In order to take advantage of the digital capabilities of cloud computing and artificial intelligence, it is crucial to connect the digital to the physical entity [7]. Thus, requiring the use of sensors to harvest data (on the physical entity) [7] in real-time and transmitted through IIoT (the communication between the digital and physical) [9, 10] throughout the product's lifecycle [7].

Furthermore, the DT can be separated into three different instances, the Digital Model (DM), Digital Shadow (DS) and Digital Twin (DT). *Digital Model* is the digital representation (model) of a non-existing physical entity, meaning that the digital entity will be the projection of a future physical entity [11]. This means that at the DM phase there is no communication between the physical and digital entity and all the processes and integration will be emulated. *Digital Shadow* differs from the DT in the sense that it does not support bidirectional communication. In the DS the data will flow automatically from the physical entity to the digital but manual from the digital entity to the physical [11]. *Digital Twin* is formed by three instances, the digital object, the physical object, and the communication between both objects[2, 12]. The digital entity is the representation of the physical entity in a digital environment and can monitor, emulate and control the behavior of the physical. In the DT, the data will flow continuously, bidirectional, and in real-time between the entities.

2.2 RAMI4.0 and Asset Administration Shell

Impacted by Industry 4.0, manufacturing industries were revolutionized and globalized, this stressed the development of a Reference Architecture Model for the Industry 4.0 (RAMI 4.0) [3, 13–15] to ensure standardization between enterprises that use I4.0 [16]. RAMI 4.0 is a service-oriented architecture that combines the fundamental elements and IT of Industry 4.0 in a structured three-dimension layer model [15, 16]. RAMI 4.0 is composed of three-axis, the product lifecycle, hierarchy levels in the factory, and the architecture. The product lifecycle is divided into type and instance. Type refers to the construction plan (i.e., development, construction, maintenance software...), covering the product lifecycle from the idea of the product to its manufacturing process [16, 17].

Within the RAMI4.0 architecture, the term Asset Administration Shell (AAS) starts to have its relevance in the technological world and can be related to DT implementation. According to [18], an "asset" can be categorized in everything that requires some sort of "connection" for an Industry 4.0 solution (e.g., machines and their components, contracts, orders, and supply materials). Moreover, the AAS will be the identification card of an asset in Industry 4.0. Furthermore, it will be responsible to provide controlled access to said information and provide a representation of the entire lifecycle of the asset [18]. The AAS aim to "enable partners in value creation networks to exchange meaningful information by conforming to a specified set of standardized elements" [19].

Besides, the AAS provides a standardization within digitized industrial production where the formatting of data/information will be according to a specified set of standardized elements [18]. Thereby, it will be composed of common standards of communication structures, rules for cyber-security, data protection, and language [18]. Furthermore, the AAS can be distinguished into three types: passive, reactive and proactive [20, 24].

- The *passive AAS* is a file written in JSON, XML, RDF, or AML that contains the catalog data of a particular asset that can be used to exchange within different partners.
- The *reactive AAS* supports the use of API to create a client/server connection, thus the content is made available using an interface.
- The *proactive AAS* in addition to supporting the API, client/server connection can ensure the desired behavior of the autonomous systems by containing decision-making skills.

2.3 International Data Spaces

International Data Spaces (IDS) initiative has the goal to create a safe data space in which industry enterprises can safely share their data assets [25] with different enterprises within the IDS ecosystem. IDS is defined by the IDS Association as a "Distributed network of Data Endpoints (i.e., instantiations of the IDS Connector), allowing a secure exchange of data and guaranteeing Data Sovereignty" [26]. Moreover, IDS allows establishing a secure connection between IDS connectors in which data is shared safely and can only be accessed according to the terms defined by the participants (typically the data owner and data user), guaranteeing data sovereignty for the data owner [26]. Therefore, with IDS, the implementation of smart devices can be done in a safe manner allowing innovative business processes to be created [25].

3 Power Transformer Digital Twin & Lifecycle Management

Figure 1 presents the initial design for the proposed DT to be used in this paper. This design is composed of the three main components of the DT namely, the physical object, the digital object, and the communication between both objects. Regarding the *physical object*, this component resides at the location of the PT and requires additional elements; the AAS deployments and the manager software. Whereas the data is generated from the PT and the AAS deployment will be responsible for the creation and storage of proactive AAS. Furthermore, providing an API to which the manager will be able to request said AAS files. On this API it should also be possible to distinguish different types of AAS. Moreover, it should be possible for different types of request routes to the API, namely, requesting maintenance AAS or operation AAS. The software manager will then be responsible for pushing the AAS to the IDS connector from the provider of data that will afterward publish the contents to the IDS connector from the consumer of data. The *communication layer*, according to the DT requirements, must support bidirectional communication. Once the AAS contents are published to the IDS connector from the consumer, the secure data exchange between the data provider and consumer is completed, ensuring data sovereignty and ownership according to the terms defined by both participants, thereby the AAS contents are ready to be used by the digital services provider.

Referring to the DT components, this will refer to the *digital object*, in which data will be processed and emulated onto a copy of the transformer in a digital environment capable of ensuring predictive maintenance and improving the overall performance of the transformer. Data will be displayed in interactive dashboards. Thus, supporting the decision-making process of the machine performance, capable of remotely and automatically controlling the transformer processes.

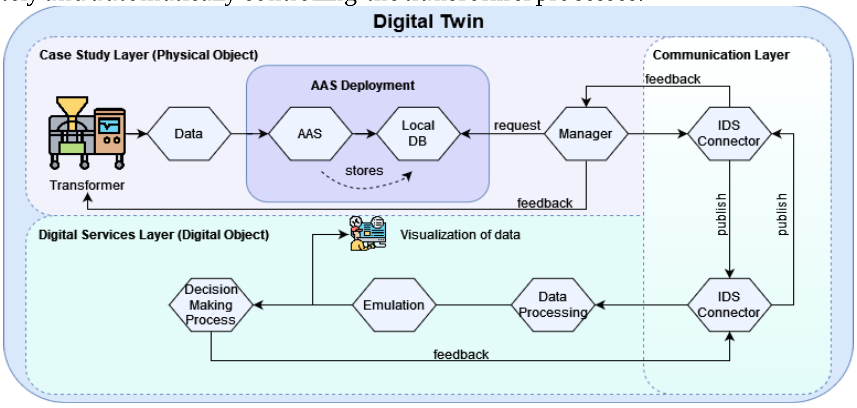


Fig. 1. Digital Twin design for a power transformer

Therein surges the premise of following the PT along its entire lifecycle supported by digital data-driven services built on top of the digital twin platform including beginning of life, from conceptualization, definition and commissioning, middle of life, covering PT operation, usage and maintenance, and end of life, with disassembly, recycling and remanufacturing. It is then possible to distinguish the concept on two lifecycles connected between each other through stages: PT lifecycle & DT lifecycle.

1. In the *design* stage, through the *development of a digital model*, it is possible to visualize and materialize PTs in a more efficient and informed manner by leveraging historical data from previous designs, and from PTs in different stages of the lifecycle.
2. *Production stage*, the *digital model instantiation* can validate the PT concepts and designs in a safe digital environment and provide high fidelity models to optimize the product assembly process.
3. *Commissioning* stage, the *physical and digital object connection* can be eased with the DM to test the integration of the PT in the manufacturing process, reducing the risk of an unsuccessful implementation and the need for physical testing procedures.
4. In the *middle-of-life* stage, the *data-driven digital services* are provided by a set of data-driven tools that, in a product-service business model, generate added value for customers.

5. *End-of-life* refers to the tail end of the PT lifecycle and includes the *product status assurance* of the different components that can be reclaimed for refurbishing or remanufacturing and, finally, disposal.

Data, information and knowledge recovered throughout all these phases by the DT should be integrated and analyzing fueling other instances of the DT, in different stages of the lifecycle with historical data, crucial for continuous improvement.

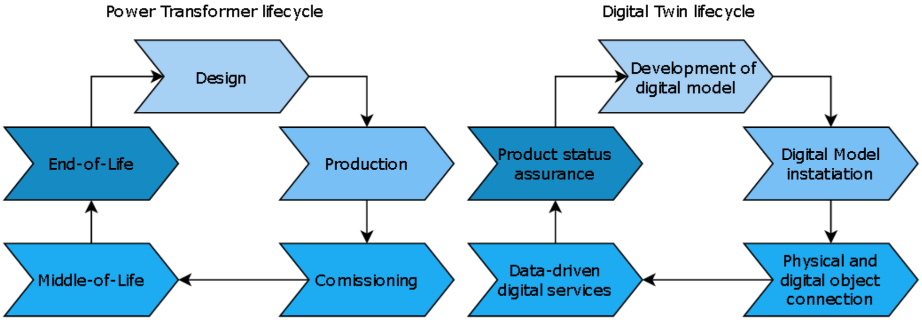


Fig. 2. Relationship between the PT & DT lifecycle

4 Framework Presentation

4.1 Digital Twin Platform

Digital platform (DP) is a term that is used in many fields of research. Authors such as [27] and [28] present a list of definitions that, from a management and information systems perspective, range from the technical point of view to socio-technical focused conceptualizations that define platforms as a set of technical elements (software and hardware) along with its associated organizational processes and standards. From this socio-technical perspective [29] summarizes the characteristics that differentiate platforms into four properties: (i) compressed evolution as the capacity of platforms to shorten the period required to observe different market dynamics; (ii) evolution that predicts long-term suitability; (iii) the capacity to harness external disruptions; and (iv) the ability of architecture and governance to shape evolution. The flexibility these four properties embed DPs with has positioned them as the preferred infrastructure for developing a new paradigm of business models centered around customers, suppliers, and developers' aggregation [30]. The resulting ecosystem is then able to generate externalities and synergies where the joint value creation is greater than the sum of the value created by individual businesses [31].

[32] argue that a platform is an architecturally innovative means of sharing assets such as algorithms, data, and functions with ecosystems of people, businesses, and things. Our vision for a digital twin platform brings together the DPs as the infrastructure to support the DT as the core architectural element for (i) managing and processing the historical data collected from the multiple working instances of DTs, and (ii) managing and integrating design information (models, specifications, design data,

among others) [30]. Furthermore, by leveraging the multi-sided platform model this architecture has implications on both the intra and inter-organizational level: from an intra-organizational perspective, this platform provides DT-based tools to support the entire PLM; while from an inter-organizational perspective, it is able to generate a market of products and services that, by its data-rich nature, can be leveraged to fuel the development of new business models centered around product-service systems.

Figure 3 presents an initial architecture that realizes our vision of the DT as the platform's central component and illustrates the essential components while comparing it to the reference ISO/DIS 23247-2 DT framework for manufacturing.

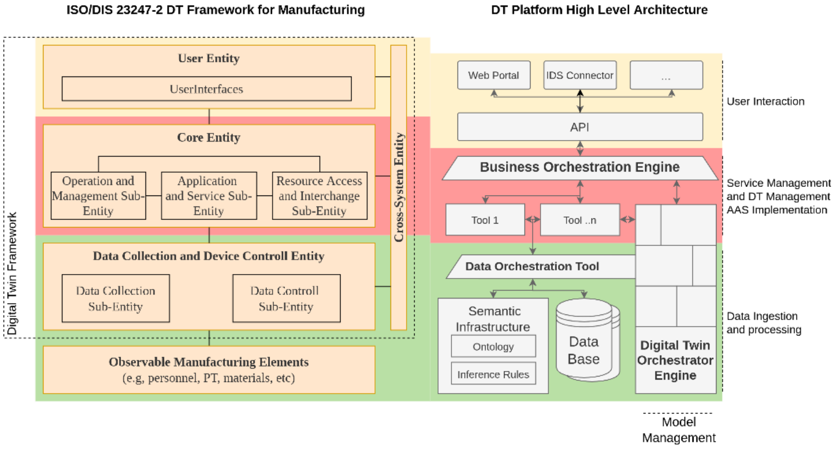


Fig. 3. Comparison of DT platform architecture and the ISO/DIS 23247-2 DT framework for manufacturing

Placed at the core of the DP, the Digital Twin Orchestrator Engine (DTOE) is the component that serves as the core for the management and orchestration of multiple instances of the DT. A direct link between platform services and the DTOE allows for a shorter latency between platform services and the virtual and physical realities of products/services. The DTOE is responsible for the dual role of: (i) centralizing the management of the DT components by providing the platform with structured interfaces for direct control, and thus influencing both virtual and physical components of multiple instances of a product or service; and (ii) interface with the remaining data layer components in order to structure and integrate design and operational data and information.

The tools layer leverages the data and information available from the data layer, to deliver the platform's core functionalities. Ranging from the standard platform services to generate the ecosystem, such as user and transaction management, to sets of data-driven tools that fuel the PLM from product development to disassembly. The BOE is responsible for the abstraction and orchestration between the platform's different tools into a coherent set of platform services. Through the BOE, platform users can leverage and arrange the different platform-tools into different configurations to test and develop new and innovative, highly customized smart PSS that leverage the full potential of the physical/virtual interaction.

4.2 Interoperability Strategy based on IDS

Data is the fundamental element of smart manufacturing and thus crucial when intending to implement a DT platform. In order to achieve this, it is mandatory to create a secure and trusted channel of communication between the manufacturing shop floor of PT owners and the manufacturing industry of the PTs that will be responsible to provide the digital data-driven services built on top of the digital twin platform. Thereby with this statement, two major challenges arise. (i) Ensuring data sovereignty whereas the data assets generated by the PT remain in control of the PT owner even when used by the PT manufacturer to provide the digital data-driven services. (ii) Ensuring data security means that the data assets exchanges between the PT owner and the PT manufacturer are secure and protected. Based on this, this paper conducts an interoperability strategy based on the IDS to face these two major challenges. IDS allows establishing a secure connection between IDS connectors. Based on this, it is possible to adapt the communication layer of the DT with the inclusion of IDS connectors, and thus the innovative digital data-driven digital services are supported by a secure and reliable communication infrastructure.

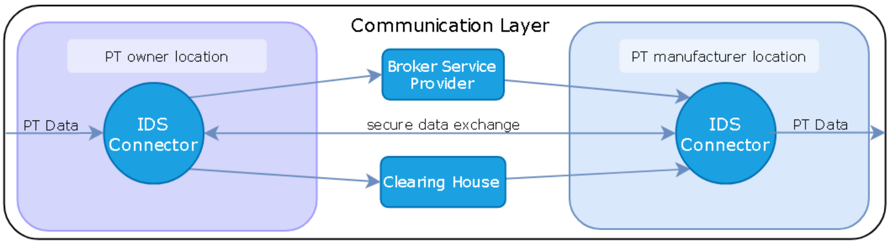


Fig. 4. Reformulated communication layer leveraging the IDS initiative

As shown in Figure 4 data assets generated from the PT are pushed to the provider IDS connector (PT owner). There, the provider IDS connector publishes the data assets to the consumer IDS connector (PT manufacturer) in which the data assets are ready to be used by the digital data-driven services. The identity provider is capable of validating the identity of the desired target IDS connector, thus, avoiding unauthorized access to data.

Furthermore, in the Clearing House, the PT owner and the PT manufacturer log details regarding transitions of data assets. The usage of this module enables the evolving entities to resolve conflicts and provide financial reports for billing purposes. On top of that, the data exchanges within the IDS ecosystem are supported by a contractual agreement between the evolving entities, thereby, the PT owner can limit how their data assets are used by the PT manufacturer when providing the digital data-driven services. Data sovereignty is therefore ensured for the data owner.

4.3 Transformer AAS & Ontologies

The AAS will serve as the identification card of the power transformer and is responsible for providing a digital representation of the PT throughout its entire lifecycle. Furthermore, by utilizing the AAS it is possible to achieve a common understanding within digitized industrial production enterprises. The AAS also supports the use of external dictionaries such as eCl@ss and IEC CDD easing the process of assigning semantic descriptions to the AAS properties. Figure 5 displays the simplified AAS metamodel, in sum, an asset administration shell can be composed of multiple sub models, each sub model refers to a specific domain, and each sub model can be composed of multiple sub model elements and each sub model element can have one or more qualifier.

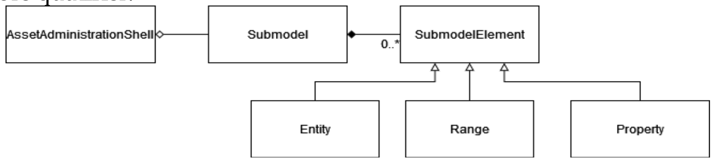
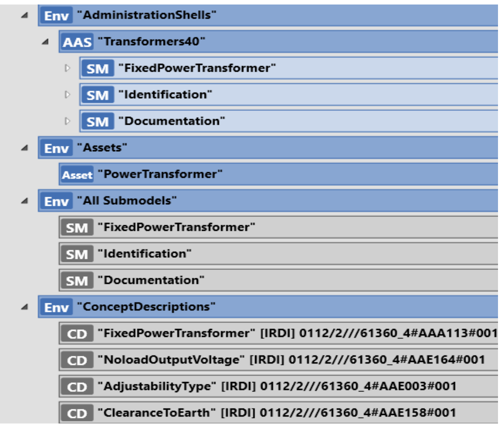


Fig. 5. Simplified Asset Administration Metamodel

At the time of this writing, there are no frameworks developed capable of deploying proactive AAS, so as proof-of-concept was developed a passive AAS of a power transformer created with the IEC CDD dictionary in the software AASX Package Explorer as shown in Figure 6.



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Env "AdministrationShells"
    AAS "Transformers40"
        SM "FixedPowerTransformer"
        SM "Identification"
        SM "Documentation"
Env "Assets"
    Asset "PowerTransformer"
Env "All Submodels"
    SM "FixedPowerTransformer"
    SM "Identification"
    SM "Documentation"
Env "ConceptDescriptions"
    CD "FixedPowerTransformer" [IRDI] 0112/2///61360_4#AAA113#001
    CD "NoloadOutputVoltage" [IRDI] 0112/2///61360_4#AAE164#001
    CD "AdjustabilityType" [IRDI] 0112/2///61360_4#AAE003#001
    CD "ClearanceToEarth" [IRDI] 0112/2///61360_4#AAE158#001
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Fig. 6. Passive AAS for a fixed power transformer

This AAS is composed of three sub models, FixedPowerTransformers contains the technical data, identification contains data regarding the manufacturer of the PT, and documentation containing documents associated with the PT. Furthermore, ConceptDescriptions includes the definition of variables according to the IEC CDD, thus, ensuring semantic interoperability.

5 Use Case Presentation

Current power transformer development processes remain traditional in nature, relying on document-based information exchange and a set of PLM and simulation tools that are not interconnected [30]. We believe that our DT and the DT enabled DP visions described above when adopted and applied to the PT lifecycle can effectively shape its technologies and processes towards the Industry 4.0 standards. In partnership with a Portuguese company in the energy field, the platform is under active development to deliver to key company stakeholders a set of core tools and services to support the different stages of the PT lifecycle.

Supporting the conceptual design phase, the DT Platform can provide the engineering departments with reference PT designs that can serve as blueprints for developing new PT that fit a new customer's specific needs and requirements. Going further and leveraging the semantic descriptions of all the components of the PT and the datasets associated with all the components themselves, this new design can be tested and validated using simulation tools that leverage data gathered from real-world conditions of applications in previous projects. In the detailed design phases, the ability to detect design non-conformities based on operational insights, requirements, and rules simulation of critical operating conditions can be managed through the platform, providing the organization with critical information that will further optimize future PT development processes.

From an inter-organizational perspective, new value propositions will be leveraged from the DT platform, enabling the development of a new business model supported by it. Supported by this DT platform, the enterprise will be able to streamline PT development, resulting in reductions in cost and lead time, improve the design by certifying that it meets requirements and expectations, improve knowledge capture and sharing, and finally, add additional value to the product which will result in a better offering altogether.

6 Conclusions

Power transformers sector has also been evolving to develop smart transformers for the future, capable of providing the digital capabilities to leverage new services and features that follow its entire life cycle, from the design and manufacturing to the use and dismantling/ recycling. In this sense, there is a strong opportunity to develop and adopt the Digital Twin concept to implement this vision. Nevertheless, there are a series of issues that arise to guarantee its full implementation. The first issue is related to data and knowledge management, in a comprehensive and effective way. The second issue is related to data governance and data sovereignty, between the different actors of the value chain and along the distinct stages of the product life cycle. To cope with these challenges, this paper proposes a new architecture for the management of digital twin and its instances. For this architecture, both Asset Administration Shell (AAS), the International Data Spaces (IDS) and an ontological data representation of the power transformer, based on standards, is proposed to deal with the issues previously presented. Finally, a real use case from a Portuguese power transformer producer is presented, as well as the main benefits of this innovative approach for its business model and services enhancement.

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