The Digital Twin as a Knowledge-Based Engineering Enabler for Product Development

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Abstract. Industry 4.0 encompasses technologies that generate valuable insights from large data exchange networks. This, along with the growing digitalization of organizational information and knowledge, turns these assets into a valuable resource for product and process improvement and optimization. In this context, Knowledge-based Engineering (KBE) is presented as a way to efficiently capture and reuse organizational knowledge. As such, this work conceptualizes the Digital Twin, emerging technology as a KBE enabling application that employs organizational knowledge as the driving force behind product development. To this end, power transformer development is used as a case study.

Keywords: Information management · Knowledge management · Knowledge-based engineering · Digital twin · Power transformer development

1 Introduction

Industry 4.0 has made it possible for information and knowledge to become the most valuable resource in an organization, as the integration of Information and Communication Technologies with physical devices through cyber-physical systems and the Internet of Things results in the creation of large data exchange networks that generate valuable insights for product development and for product life-cycle management.

Moreover, the growing volume, variety and velocity of the information generated during the product lifecycle, which includes product requirements and specifications, design models and data related to product calculation and testing, production and operation, can be an important knowledge base for an organization, assisting design teams and managers in decision-making, which in turn improves product design, reduces lead time and decreases monetary costs.

Consequently, the more efficient and effective planning of strategies and instruments that make the capture, description, organization, and retrieval of information generated during the lifecycle of a product, is a crucial factor to obtain benefits from organizational knowledge.

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This can be achieved by implementing Knowledge-based engineering (KBE) in product development processes. KBE refers to the knowledge management (KM) tasks of capturing, storing, modeling, and sharing of organizational knowledge, both in explicit form (such as documents or models) and in tacit form (present in the minds of employees and materialized in e.g. collaborative work). This knowledge can then be coded in computational systems, enabling the automation of repetitive design tasks [1].

The concept of KBE was first introduced in the 1980s as part of a new set of software applications called Knowledge-based Engineering Systems. These systems, which are generally integrated with CAD software, capture organizational knowledge, and encourage its reuse, allowing for the automatization of routine design tasks [1]. Thus, Knowledge-based Engineering is the implementation of knowledge management methods and instruments, which support computational systems that make organizational knowledge the centerpiece of engineering design.

KBE is frequently applied in product design, especially in the automotive and aerospace industry. It has yielded results in the reduction of lead time, with implementation cases achieving results of up to 75% reduction in process duration [2]. Furthermore, developed KBE systems also significantly decrease costs and improve employee satisfaction, by providing features that automate design tasks, and consequently, allow for engineers to use their time in creative tasks, instead of repetitive ones [3].

Additionally, benefits related to the quality and validity of product design have also been identified, due to the ability of KBE systems to autonomously validate the design according to product restrictions and requirements, allowing for optimized products that comply with user and client requirements, to be developed faster [4].

The technological advances that characterize Industry 4.0 have also made possible the implementation of new applications that use product lifecycle information to streamline product development and improve product design. This is the case with the Digital Twin (DT), an emerging concept that virtually mirrors a physical product lifecycle, simulating its visual aspect and behavior based on bidirectional data transmission between the physical and the digital space.

In this context, this work explores the applicability of the Digital Twin concept in product development, specifically as a KBE enabling application. As a result, functionalities that employ organizational knowledge to streamline and improve product design are proposed, using power transformer (PT) development, which is characterized by intensive engineering processes that require multidisciplinary teams and expert knowledge [12], as a case study.

2 Digital Twin in Product Development

The Digital Twin is an emerging concept that was first proposed in 2002 as a conceptual model of product lifecycle management that includes a physical system and a virtual system that contains all the information related to it. Because of this, all the information generated since the creation, manufacture, operation, and disposal of the physical product also exists in its virtual copy [5].

Further definitions appear to present different points of view based on the core purpose of the DT. On one hand, some authors propose the DT as a simulation technology that can replicate all possible behaviors of a given machine or product. This perspective [6–8] appears to be attributed mainly to production line DT's, which simulate the behavior of machines on the shop floor. On the other hand, others build on the vision proposed by Grieves, specifically of the DT as an informational entity that maps the entire lifecycle of a product through the capture of virtual and physical data [9, 10].

In product development, academic literature envisions the DT as a linking element that correlates customer preferences and habits, with product design, using virtualization, simulation, and Big data captured during operation, to achieve the goal of optimizing design.

Proposed functionalities include the capability of inferring desirable design characteristics through the capture of online client feedback and information about user habits when interacting with a product. It is argued that this information can also be used by the Digital Twin to define functional requirements and synthesize design restrictions such as weight and height. Moreover, it is suggested that Digital Twin may allow the analysis of user interaction with a product through technologies such as Virtual Reality, eliminating the need for costly ethnographic observations [9].

As engineering design is carried out, the DT guarantees that the design is logically viable, functionally simple, and physically correct. The DT accomplishes this by analyzing data captured during the development process and by sensors to identify and assess the severity of design contradictions. Crucially, it is claimed that Digital Twin can help create the conceptual design itself, by allowing engineers to use contextual usage data, such as physical measured data, to compare virtual and real contexts and understand the ideal conditions for product operation.

In design validation, the Digital Twin is proposed to verify and simulate all aspects of the design, using historical and real-time data to improve virtual models progressively and iteratively. As a result, the production of a small amount of product for testing is no longer necessary, reducing financial and time costs [10].

Additionally, the Digital Twin is also seen as a potential repository of information captured and produced in all phases of the product lifecycle, because it possesses the ability to store, link and make data and information available. This streamlines design process and interconnects various areas of knowledge [11]. This idea is expanded to include data related to the customer, such as their satisfaction and feedback, and about the company, like the number of sales of each product [8].

3 Methodological Approach

The work carried out had the overall goal of developing a Digital Twin concept that employs organizational knowledge to streamline product development tasks, thus adapting development processes into a Knowledge-based engineering paradigm that is supported by the DT. This goal was achieved using the development of power transformers as a case study, specifically in a Portuguese company that operates in the energy and mobility sectors.

The methodology approach to this work was composed of 3 main steps, starting with the analysis of current Power Transformer (PT) development processes through semi-structured interviews with relevant development stakeholders, followed by the contextualization of identified bottlenecks with proposed DT features in academic literature, and finally, the definition of KBE supporting DT functionalities that address IM and KM issues that current processes exhibit.

4 Analysis of the Power Transformer Development Process

4.1 Development Stages

Through the analysis of the case study organization, 4 different stages of power transformer development could be discerned, based on product development steps defined by [9]. Each step has a set of core objectives:

Task Clarification: Identify and validate transformer requirements, as well as allocate the necessary monetary and human resources, to correspond to the customer's expectations in terms of the quality of the design, deadlines, and costs.

Engineering Design: Through engineering calculus and mechanical design, a set of electrical and mechanical specifications are developed. Engineering calculus specifies parameters such as number of coil turns and electromagnetic induction values, while mechanical design, which uses Computer Aided Design (CAD) and Computer Aided Engineering (CAE) tools, develops aspects related to the dimensions, shape, and positioning of PT components.

Virtual Verification: Design testing and validation is accomplished through a set of simulations based on computational tools (such as Finite Element Method and Computational Fluid Dynamics), techniques that assess the behavior and structural integrity of the machine, under different operating conditions. This results in a report containing recommendations for the design of the transformer, which are then followed during production.

Production: Production processes convert models created during development, into an operational machine. Production is done gradually, and after each stage, encountered problems are reported to the product development team, who adapt the PT design based on them.

4.2 Information and Knowledge Management Bottlenecks

From an information and knowledge management point of view, several bottlenecks that negatively impact PT development were identified, while other discerned issues represent missed opportunities in the employment of organizational knowledge to improve power transformer development and design. The critical issues were:

- Data generated during PT operation is not captured in a structured way.
- The search of some instructional documentation such as manuals is not possible, as this information is not fully indexed, and no metadata is associated with it.
- Sharing of acquired organizational knowledge such as lessons learned is mostly done through personalization strategies, and as such, this knowledge is not adequately formalized in any means.

Current design processes are not supported by operational data, as this data is managed mostly by the entities who control its operation. As such, the opportunity to create an important knowledge source for continuous improvement of PT design, should be exploited.

Another potential improvement in PT development can be achieved by providing a mechanism to retrieve manuals and other instructional documentation in an effortless way. Currently, this information is only accessible in design software, as a pop-up window that opens after a “Help” button is clicked.

Finally, currently implemented knowledge management instruments are focused on the sharing of knowledge through in-person interactions between engineers, and the formalization of this knowledge is not a formalized practice. The codification of this knowledge in document format could allow engineers to quickly search organizational knowledge, enabling more frequent and efficient knowledge sharing.

5 Applying the Digital Twin Concept to Power Transformer Development

The development of the DT concept resulted in a set of DT functionalities that not only help resolve bottlenecks in current processes, but also fundamentally adapt them to answer the challenges and opportunities brought by Industry 4.0.

Two types of DT features are proposed, namely those whose main purpose is to use organizational knowledge to improve PT development and operation, and those that focus on capturing and disseminating knowledge, and as such, can be seen as Knowledge Management instruments supported by the DT. The first type effectively resolves the bottleneck related to the misuse of operational sensor data, as it employs it to optimize PT design and streamline development processes, while also solving issues arising from lack of query mechanisms, by providing a centralized information base that users can use for information retrieval.

An overview of proposed DT functionalities is presented in the figure below (Fig. 1).

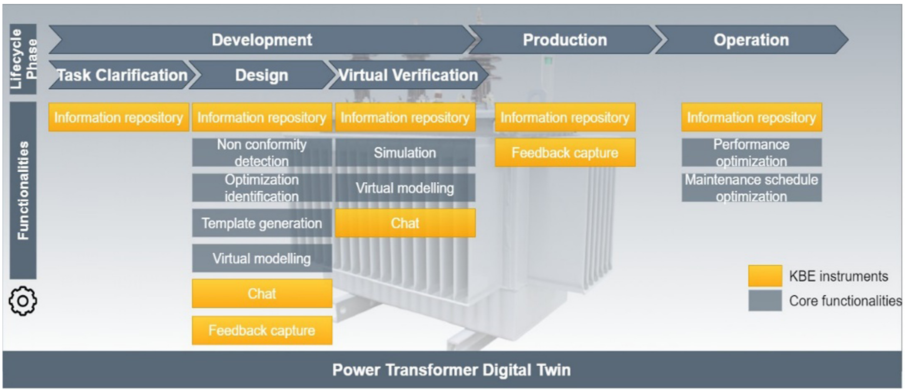

Fig. 1. Overview of the proposed Digital Twin functionalities

5.1 Design Template Generation

Several PT development processes are routine regardless of project characteristics, as although no PT conceptions are the same, machine specifications generally lead to similar designs. Because of this, historical data can be employed to automate and streamline PT development tasks.

The benefits of this opportunity can be materialized through a DT supported design workflow, composed of 4 main tasks:

1. Designers perform engineering calculus;
2. Based on calculus specifications, the DT automatically lists previous PT development projects, according to similarity;
3. Designers select a previous design to serve as a template for the current project; *and*
4. Designers adapt and refine the final solution accordingly to the specific requirements.

This process allows teams to quickly reach an initial PT design, ultimately freeing them to focus on customized design features, specific to the current project. To achieve this, the DT requires Artificial Intelligence algorithms to recognize similarities between PT specifications, and previous PT designs.

5.2 Design Nonconformity and Optimization Detection

In the previously described workflow, DT generated design templates will usually have minor inconsistencies with current project specifications, and thus, the DT should also be able to identify and correct potential mistakes, inaccuracies, or nonconformities in PT design, with the following workflow:

1. DT detects design inconsistency;
2. DT alerts user; *and*
3. User manually adapts the design or commands the DT to autonomously do so.

In this point of view, the DT analyzes the PT design and checks for compliance with rules and requirements coded in the application. When a conflict is detected, the DT informs the user with the type of problem encountered, the components that are affected involved, and the norms or rules that are being infringed. Lastly, the user can opt to manually change the design or command the DT to autonomously do so.

The same process can also be employed for design optimization. To this end, sensor data, which is not useful by itself, can be captured and analyzed by the DT and integrated with other PT lifecycle information, resulting in insights regarding the optimized design of each component of the machine.

5.3 The Digital Twin as an Information Repository

Power transformer development processes involve decision making moments that require stakeholders to have access to the appropriate information that enables them to make the right decisions, especially during design. Because of this, having access to project information that influences design specifications, is crucial.

Moreover, additional decision-making support can be found in design artefacts created in previous PT development projects, as engineers can compare current project specifications with previous ones and draw insights from them.

Consequently, it is proposed that the Digital Twin include an information repository that stores all information captured in external sources, or generated by the DT, during the entire PT lifecycle. This grants to the design team a centralized information base that expands along the development and operation of the power transformer and facilitates the use of information as a major supporting tool for engineering design.

This feature has already been proposed in academic literature in works such as [9] and [11], although these authors limit the scope of DT captured information to design artefacts and other information useful for design tasks.

This work assesses the Digital Twin as an informational entity that replicates the entirety of the PT's lifecycle, and consequently, the information stored in this platform is not restricted to the development phase, instead encompassing all phases, from task clarification to disposal. As such, the DT information repository should include all information created and captured from the ideation to disposal of the power transformer.

5.4 Digital Twin Interactive Feedback

Most of the knowledge acquired in each PT development project is present solely in designers' minds, as opposed to being formalized in a physical or digital document. This entails problems such as loss of organizational knowledge due to employees leaving the organization, as well as a difficulty in identifying stakeholders who possess potentially relevant knowledge for a given design task.

Because of the DT's capability of capturing, organizing and storing PT lifecycle information, this application can also be a crucial instrument to create documents that formalize organizational knowledge and make them available to engineers during PT development.

Over the course of design tasks, product engineers often use their experience and tacit knowledge to support their decision making, with the goal of achieving a design that satisfies project requirements. As a result, the formalization of the thought process behind PT design decisions can be extremely valuable for future projects, allowing engineers to use those knowledge assets to support their own decision making, and ultimately, optimize PT design.

Considering this, it is proposed that the DT include a feature that enables both product and process engineers to leave comments regarding different aspects of PT design. In this perspective, product designers and engineers will formalize their thought process according to these steps:

1. User performs PT design;
2. User selects PT component; *and*
3. User completes *Insight* form.

Ultimately, this DT feature promotes knowledge sharing between product engineers during TP design, and between product and process engineers, during PT production.

6 The Digital Twin Information Architecture

The functionalities proposed for the power transformer Digital Twin require it to capture and generate a large amount of information over the course of the PT lifecycle. This elevates the concept of the Digital Twin as an informational entity, as it does not solely capture information that describes the physical properties of the product, but also captures every other artifact that relates to it, regardless of lifecycle phase.

As such, it is appropriate to conceptualize the Digital Twin information architecture, based on the concept developed for power transformer development.

Given the applications and functionalities attributed to the Digital Twin in the previous chapter, this platform will capture and generate information with different sources, formats, and purposes, during the power transformer lifecycle.

This information is stored and made available, not only as a way to enable PT functionalities to autonomously improve or correct non conformities in the design, but also to provide engineers with a searchable knowledge base that they can use to support and justify their decision making. Consequently, organizational knowledge becomes the foundation of the power transformer design process, thus achieving the primary goal of Knowledge-based Engineering.

The figure below presents an overview of DT information architecture (Fig. 2).

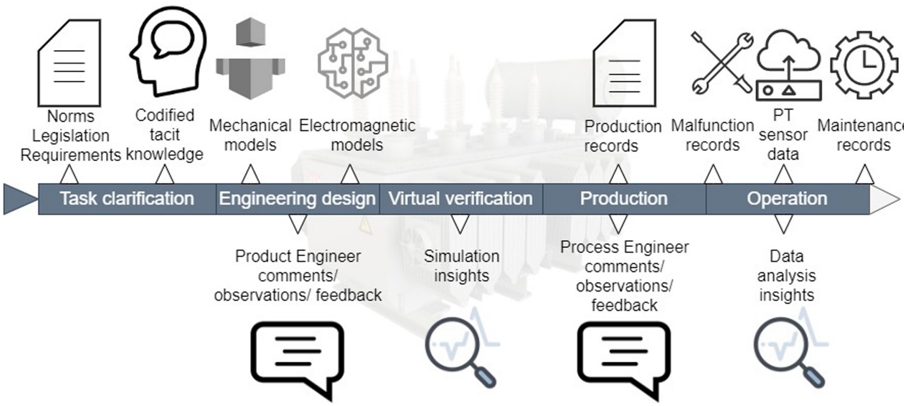

Fig. 2. Overview of the Digital Twin information architecture

6.1 DT Captured Information

The information captured by the Digital Twin originates in the task clarification, engineering design, production, and operation stages of the PT lifecycle.

During task clarification, the DT captures information that restricts PT design, such as normative and legislative rules, as well as client requirements. Furthermore, tacit knowledge present in engineers' minds is also extracted and codified in the DT platform.

In the design phase, models created in the engineering calculus and drawing tasks are captured by the DT, moreover, as the client is regularly sent design models to keep him informed of the progress of the project, his feedback is also stored in the DT. Accordingly, during the design and production phases, the feedback of product and process engineers is also captured.

Finally, as PT operation begins, so does the capture of sensor data by the Digital Twin, which stores it through data warehouse technology and analyzes it with data analysis algorithms and artificial intelligence.

6.2 DT Generated Information

Digital Twin generated information refers to all information that is autonomously created by DT functionalities and tools, instead of being captured in external sources, or created by stakeholder feedback. This type of information is mostly generated by the data analysis and simulation features of the DT, and as such, it involves the virtual verification and operation lifecycle stages.

In the virtual verification stage, the DT produces insights regarding the performance of each component when it is tested in several working conditions and parameters, and during operation, further insights are generated from sensor data analysis.

7 Conclusion

Through the analysis of power transformer development processes, a Digital Twin concept that actively uses organizational knowledge to improve PT design and streamline development tasks, as well as provides features that motivate knowledge sharing, is proposed. Among defined features are the ability to use historical and operational data to create design templates, the possibility of describing the thought process behind design decisions, and the availability of an information repository that users can query to retrieve product lifecycle information.

Furthermore, the information architecture of the DT platform, which includes all information that the application will capture and generate during the product lifecycle, is described.

As such, this paper provides an initial conceptualization of the DT when applied to PT development. Further work is necessary in the areas of requirements elicitation, KM, and software development, to achieve a fully operational DT.

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