

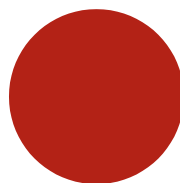
MESTRADO EM CIÊNCIA DA INFORMAÇÃO

DATA-DRIVEN KNOWLEDGE-BASED ENGINEERING SUPPORTED BY THE DIGITAL TWIN

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Data-driven Knowledge-Based Engineering supported
by the Digital Twin

Dissertation carried out under the Master in Information Science scope, supervised
by Professor António Lucas Soares and co-supervised by Diogo Henrique Silva.

Faculty of Engineering and Faculty of Arts
University of Porto

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*“Vision without action is a daydream.
Action without vision is a nightmare.”*

Japanese proverb

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Abstract

At Efacec, turning PT compatible with Industry 4.0 trends is challenging since information is not shared efficiently abroad for stakeholders to make better decisions. Creative and high-value stakeholders spend their time on low-value repetitive tasks and fail to implement authentic innovation practices.

Moreover, during the lifecycle of a Power Transformer, a large amount of data is generated, from its concept, design, manufacturing, and operation until disposal. The difficulty is that the current product design and engineering processes are not designed to take advantage of the rich data available through implementing the Digital Twin concept and their potential for knowledge extraction.

In this context, this work aims to study how the availability of data and information provided through the Digital Twin approach will impact product design and engineering processes. Information and data analytical methods become valuable components in organisations, enabling knowledge dissemination and collaboration among stakeholders to address better performance in developing new customisable products.

Considering the features proposed for the lifecycle of the Power Transformer, there is a complementarity between Knowledge-Based Engineering and Digital Twin. The latter serves as a support platform for Knowledge-Based Engineering processes. It comes particularly from Digital Twin's ability to act as a recommendation system, storing and providing information that assists the engineer in defining functional requirements and conforming them to the objectives of the project.

The case study research method was employed as an empirical inquiry. This method was an appropriate research design when it is necessary to obtain holistic, concrete, contextual, and in-depth knowledge about specific real-world key characteristics, meanings, and implications of a subject.

Achieving the research aims will contribute to assessing the impact on product design and engineering processes of the availability of data and information provided through the Digital Twin. The organisation will then have conditions to reach a new context characterised by volatile processes, whose trends and customers change rapidly, demanding custom yet fast design approaches.

Keywords: Information Management, Knowledge Management, Knowledge-based Engineering, Digital Twin, Power Transformer development, Industry 4.0

List of figures

Figure 1 - Objective tree of the dissertation.	19
Figure 2 - Time and design cycle comparison between traditional and KBE-enabled design (Emberey et al. 2007).....	26
Figure 3 - Developing lifecycle of KBE according to MOKA (Stokes 2001).	28
Figure 4 - The KBE development lifecycle according to MOKA (Stokes 2001).....	30
Figure 5 - The CommonKADS model suite with six models (Schreiber et al. 1999).	32
Figure 6 - Conceptual ideal for PLM. Dr. Michael Grieves, University of Michigan, Lurie Engineering Center, Dec 3, 2002.	34
Figure 7 - Waves and simulation as core functionality for DT (Weyer et al. 2016).....	35
Figure 8 - The three-dimension model for the DT (Gabor et al. 2016).	36
Figure 9 - The fusion of DT, Big Data and services in manufacturing, representing the three-dimension model (Qi and Tao 2018).	37
Figure 10 - Five-dimension model for the DT (Tao and Zhang 2017).....	37
Figure 11 - The lifecycle of a computer tomography scanner and its DT, from design to dismissal (Barricelli, Casiraghi, and Fogli 2019).	39
Figure 12 - User Stories with requirements and desires in each lifecycle phase (Riedelsheimer, Dorfhuber, and Stark 2020).	40
Figure 13 - CDT functional architecture layers and lifecycle stages plane (Zheng, Lu, and Kiritsis 2021).	46
Figure 14 - (a) The Blockchain utilised to record the data of DT of the turbine; (b) DM platform for DT of the turbine (Huang et al. 2020).....	46
Figure 15 - Strategic goals driving the STS-D (Rebentisch et al. 2021).....	48
Figure 16 - Socio-Technical System Analysis Framework for DTs (Rebentisch et al. 2021).	49
Figure 17 - Full products & service portfolio.	66
Figure 18 - The Power Transformer.	67
Figure 19 - TRf4.0 project overview. TRF4.0 consortium, internal document.....	68
Figure 20 - An integrated model for knowledge creation and dissemination. (a) Knowledge consumption, composition, and dissemination from and for the teams; (b) Tacit and implicit Knowledge consumption, co-creation and dissemination.	96
Figure 21 - Typical business questions performed to the CE by workers.....	99
Figure 22 - The delivered answers and insights to the workers.	100
Figure 23 - Worker searching for information regarding PTs from a specific customer. ...	103
Figure 24 - Worker receiving the information package.	104

Figure 25 - Worker updating data for specific lifecycle stages.....	105
Figure 26 - Events updating data for specific lifecycle stages.	106
Figure 27 - DT failure detection and automatic maintenance schedule notification.....	107
Figure 28 - Worker checking and interacting with the DT.....	107

List of tables

Table 1 - Keywords and search conditions for DT.....	21
Table 2 - Keywords and search conditions for KBE.	22
Table 3 - Keywords and search conditions for DT and KBE.	22
Table 4 - Selected databases.....	22
Table 5 - Focus group schedule for KBE concept.....	56
Table 6 - Focus group schedule for LCM concept.	56
Table 7 - Focus group schedule for PSS concept.	56
Table 8 - KM processes summary.	86
Table 9 - KM from the perspective of processes and analytical culture summary.	86
Table 10 - Technology-focused on IM summary.....	87
Table 11 - Technology-focused on applications, software, and IT management summary. ...	88
Table 12 - Engineering processes focused on the PT lifecycle summary.	89

List of abbreviations and acronyms

ADT - Airframe Digital Twin

AI - Artificial Intelligence

AM - Additive Manufacturing

BOE - Business Orchestration Engine

BOL - Beginning-Of-Life

BSC - Balanced Scorecard

BU - Business Unit

CAD - Computer-Aided Design

CDT - Cognitive Digital Twin

CE - Cognitive Engine

CPS - Cyber-Physical Systems

CT - Cognitive Twin

DDoS - Distributed Denial of Service

DM - Data Management

DL - Data Lake

DOT - Data Orchestration Tool

DT - Digital Twin

DTOE - Digital Twin Orchestrator Engine

EOL - End-Of-Life

FML - Fibre-Metal Laminate

ICT - Information and Communication Technologies

IM - Information Management

IoT - Internet of Things

IS - Information Systems

IT - Information Technology
KBE - Knowledge-Based Engineering
KM - Knowledge Management
LCM - Lifecycle Management
MBSE - Model-Based Systems Engineering
ML - Machine Learning
MMG - Multi-Model Generator
MML - MOKA Modelling Language
MOL - Middle-Of-Life
NASA - National Aeronautics and Space Administration
OLAP - Online Analytical Processing
OLTP - Online Transaction Processing
PDM - Product Data Management
PLM - Product Lifecycle Management
POC - Proof-Of-Concept
PSS - Product-Service Systems
Q&A - Question and Answer
PT - Power Transformer
RUL - Remaining Useful Life
SCM - Supply Chain Management
SMEs - Small and Medium Enterprises
SoS - System of Systems
STS-D - Socio-Technical Systems Design
TRF4.0 - Transformer 4.0
UML - Universal Modelling Language

Table of contents

1. Introduction	16
1.1. Context and motivation	16
1.2. Problem description	17
1.3. Objectives and expected results	18
1.4. Dissertation structure	19
2. Literature review	21
2.1. Methodology	21
2.2. The notion of Knowledge-Based Engineering	23
2.2.1. KBE project applications and outcomes	26
2.2.2. KBE implementation	27
2.2.3. KBE methodologies	28
2.2.3.1. MOKA	28
2.2.3.2. CommonKADS	31
2.2.3.3. Other methodologies	33
2.3. The notion of the Digital Twin	34
2.3.1. Data Twin project applications and outcomes	38
2.3.2. Digital Twin's potential features in the product lifecycle	39
2.3.2.1. Application in the design phase	40
2.3.2.2. Application in the manufacturing phase	41
2.3.2.3. Application in the service phase	42
2.3.2.4. Application in the after-service phase	43
2.3.3. Emerging topics	44
2.3.3.1. The Cognitive Digital Twin	44
2.3.3.2. Digital Twin and Blockchain	46
2.3.3.3. Digital Twin and Socio-Technical Systems Design	48
2.4. Knowledge-Based Engineering and Digital Twin	49
2.5. Final considerations	50
3. Methodological approach	52
3.1. Overall methodology structure	52
3.2. Methods employed for data collection	53
3.2.1. Collect and analysis of existing documentation and partial results	53
3.2.1.1. Vision definition	53
3.2.1.1.1. First workshop briefing	53

3.2.1.2.	High-level requirements	54
3.2.1.2.1.	Second workshop briefing	55
3.2.1.2.2.	Focus groups briefing	55
3.2.2.	Collect data using focus groups and semi-structured interviews	57
3.2.2.1.	Focus group	57
3.2.2.2.	Interviews	58
3.2.2.3.	High-level engineering documents	60
3.2.3.	Data triangulation	61
3.3	Result analysis and requirements development	62
4.	Case study description	63
4.1.	The organisation description	63
4.2.	The Transformer Business Unit	63
4.2.1.	Business Unit organisation	63
4.2.2.	Transformers projects development dynamics	65
4.3.	Products & services portfolio	65
4.4.	The Power Transformer	66
4.5.	The Transformer 4.0 project	67
5.	Results	69
5.1.	Research results from previous project tasks	69
5.1.1.	Vision definition	69
5.1.2.	High-level requirements	70
5.2.	Research results for engineering processes and lifecycle	71
5.2.1.	Focus group	71
5.2.1.1.	Knowledge Management	71
5.2.1.2.	Information Management	72
5.2.1.3.	Collaboration	73
5.2.1.4.	Action Plans	73
5.2.1.5.	Engineering Processes	74
5.2.2.	Interviews	74
5.2.2.1.	Position in the organisation	74
5.2.2.2.	Knowledge Management Processes	75
5.2.2.3.	KM from the perspective of processes and analytical culture	77
5.2.2.4.	Technology-focused on Information Management	78
5.2.2.5.	Technology-focused on applications, software and IT management	80
5.2.2.6.	Engineering processes focused on the PT's lifecycle	81

5.2.2.6.1.	Beginning-Of-Life stage.....	81
5.2.2.6.2.	Middle-Of-Life stage	81
5.2.2.6.3.	End-Of-Life stage	82
5.2.3.	High-level engineering processes analysis procedures	82
5.2.3.1.	Project requirement analysis	82
5.2.3.2.	Simulation integration framework	83
5.3.	Results Summary	84
5.3.1.	Vision definition and high-level requirements	84
5.3.2.	Engineering processes and lifecycle	85
6.	Implementing the Digital Twin concept.....	90
6.1.	The Power Transformer virtual modelling.....	90
6.2.	Defining a query mechanism for Digital Twin information.....	91
6.2.1.	Describing information for Digital Twin	92
6.2.2.	Defining facets	93
6.3.	Creation and dissemination of knowledge from AI services.....	95
6.3.1.	Use cases for Cognitive Engine.....	99
6.4.	The requirements for redesigned knowledge processes	101
6.4.1.	Knowledge Management requirements	102
6.4.2.	Lifecycle requirements.....	102
6.5.	Digital Twin data and Information Management model.....	102
6.5.1.	Use cases for Knowledge-Based Engineering processes	102
6.6.	The impact on product design and engineering processes	108
7.	Conclusions	109
7.1.	Key findings.....	109
7.2.	Limitations of the research	114
7.3.	Future research	115
8.	References	116
	Appendices.....	126
	Appendix 1 - Focus group full agenda and structure.....	127
	Appendix 2 - Questionnaire for interviews.....	128
	Appendix 3 - Engineering processes faceted classification	138
	Appendix 4 - Knowledge Management requirements.	145
	Appendix 5 - Lifecycle requirements.....	150
	Appendix 6 - Key impacts and related risks.....	156
	Annexes	161

Annex 1 - First workshop full agenda and structure. TRF4.0 consortium, internal document.....	162
Annex 2 - Second workshop full agenda and structure. TRF4.0 consortium, internal document.....	163
Annex 3 - User stories samples. TRF4.0 consortium, internal document.	164
Annex 4 - Focus group full agenda and structure for KBE concept. TRF4.0 consortium, internal document.....	165
Annex 5 - Focus group full agenda and structure for LCM concept. TRF4.0 consortium, internal document.....	166
Annex 6 - Focus group full agenda and structure for PSS concept. TRF4.0 consortium, internal document.....	167
Annex 7 - Project requirement: documentation analysis. TRF4.0 consortium, internal document. TRF4.0 consortium, internal document.	168
Annex 8 - First workshop summary of topics regarding KBE. TRF4.0 consortium, internal document.....	169
Annex 9 - First workshop summary of topics regarding LCM. TRF4.0 consortium, internal document.....	170
Annex 10 - Second workshop and focus group summary regarding KBE. TRF4.0 consortium, internal document.	171
Annex 11 - Second workshop and focus group summary regarding LCM. TRF4.0 consortium, internal document.	173

1. Introduction

1.1. Context and motivation

Due to its fast development, technology has become a vital catalyst for streamlining organisation transformation in recent years, allowing the integration of different digital technologies across all organisational structures, changing how the business operates and delivering value to all stakeholders. Since the end of the twentieth century, major industries have included new technologies, methods, and efficient processes in their strategic plans to develop better products and improve their competitiveness.

The concept of Industry 4.0 emerged to contextualise the fast evolution of industries, technology, and societal patterns and methods in the twenty-first century. The main objective of Industry 4.0 is to promote the intelligent networking of products and processes along the value chain, permitting it to use the organisational processes more efficiently to create goods and services, enhancing customer benefit by offering them novel products and services (Anderl 2014) (Bartevyan 2015). From the technology point of view, Industry 4.0 encompasses developing and integrating innovative Information and Communication Technologies (ICT) into the industries, such as the Internet of Things (IoT), Cyber-Physical Systems (CPS) and Cloud Computing, among others.

Industry 4.0 is a known concept in manufacturing, and this structure is used to optimise production and increase flexibility and efficiency within an innovative factory environment. The value chain can be transformed by Industry 4.0, which forces businesses to reconsider how they conduct business, creating a driving force to implement digital transformation in the organisations to succeed in the new environment. The digital transformation also demands a cultural change, where the organisation must defy long ago established processes and, at the same time, develop an experimental failure tolerance culture that encourages learning through experimentation.

In this context, information and data analytical methods become valuable components in organisations, enabling knowledge dissemination and collaboration among stakeholders to address better performance in developing new customisable products. Manufacturing employs the Knowledge-Based Engineering (KBE) approach to obtain the best practices in product design, expert knowledge and experience into an organisational knowledge base (Chapman and Pinfold 1999).

Digital Twin (DT) is an emerging concept that takes advantage of Industry 4.0 technologies and is designed to be a comprehensive virtual representation of a physical system, enabling

data exchange between the counterparts. In addition, the DT intends to collect all data and integrate it into a single source, fostering assertive analysis of optimising Product Lifecycle Management (PLM) through continuous diagnosis and performance analysis. The DT concept and its technological implementation are closely related to product design and engineering (Zhuang et al. 2017). Moreover, the joint and articulated addition of DT with KBE can positively impact the development of the PT and the organisation's recognition as a leader, enhancing its reputation in the market (Rebentisch et al. 2021).

The organisation object of study of this dissertation is Efacec, a Portuguese company with an extensive international presence in Power Products, Systems, and Electric Mobility technology. It is one of the world leaders in designing and manufacturing Power Transformers (PT). The organisation's objective is to lead the movement in digital transformation, ease product-life management, and develop Knowledge Management (KM) strategies, allowing the organisation to create an environment where stakeholders share knowledge, collaborate, and make decisions efficiently.

1.2. Problem description

At Efacec, turning PT compatible with Industry 4.0 trends is challenging, as information is not shared efficiently between stakeholders to improve the design process. During the lifecycle of a PT, a large amount of data is generated, from its concept, design, manufacturing, and operation until disposal.

This pertinent information is not leveraged by the organisation, so opportunities for optimising PT performance are lost due to the lack of digitalisation of the product lifecycle. Moreover, the current product design and engineering processes are not designed to take advantage of the rich data and information available. Consequently, creative and high-value stakeholders spend their time on low-value repetitive tasks and fail to implement authentic innovation practices.

Hence, developing strategies and methodologies for gathering, describing, organising, and recovering information generated by the PT's lifecycle is vital for engineers to complement their knowledge and experience with the organisational knowledge captured over time.

The KBE is beneficial for identifying and standardising design decisions. Its methods enable interdisciplinary sharing of information, documentation, and knowledge to establish a collaborative design. The DT concept implementation is also expected to improve product performance and its potential for knowledge extraction.

1.3. Objectives and expected results

The dissertation research question to be answered is: How can a DT-based data and information architecture improve the PT design and engineering knowledge-based processes? Furthermore, defining requirements for managing captured data from previous development processes and identifying features the platform should contain to foster collaboration between process and product engineers. In this context, this work will explore the case study of the PT produced by Efacec, and the background will be the Transformer 4.0 (TRF4.0) project, which aims to digitalise PT's lifecycle.

The specific objectives for this dissertation are:

- Analyse the existing product design and engineering processes;
- Characterise the creation and dissemination of knowledge obtained from the use of Artificial Intelligence (AI) tools that explore the data from the DT;
- Specify the requirements for redesigned knowledge processes leveraged in new data and information structures centred in the DT;
- Refine the DT data and Information Management (IM) model included in the DT digital platform to meet the requirements of the knowledge-based processes;
- Develop a Proof-Of-Concept (POC) for a part of a process, including a knowledge lifecycle model, from data to knowledge, methods for collaboration fostering knowledge sharing, and new information/knowledge practices;
- Assess the impact on product design and engineering processes of the availability of data and information provided through the DT.

Achieving these objectives will contribute to adapting the PT design process to a new context characterised by volatile processes, whose trends and customers change rapidly, demanding custom yet fast design approaches. In figure 1, the related objectives are classified and organised hierarchically.

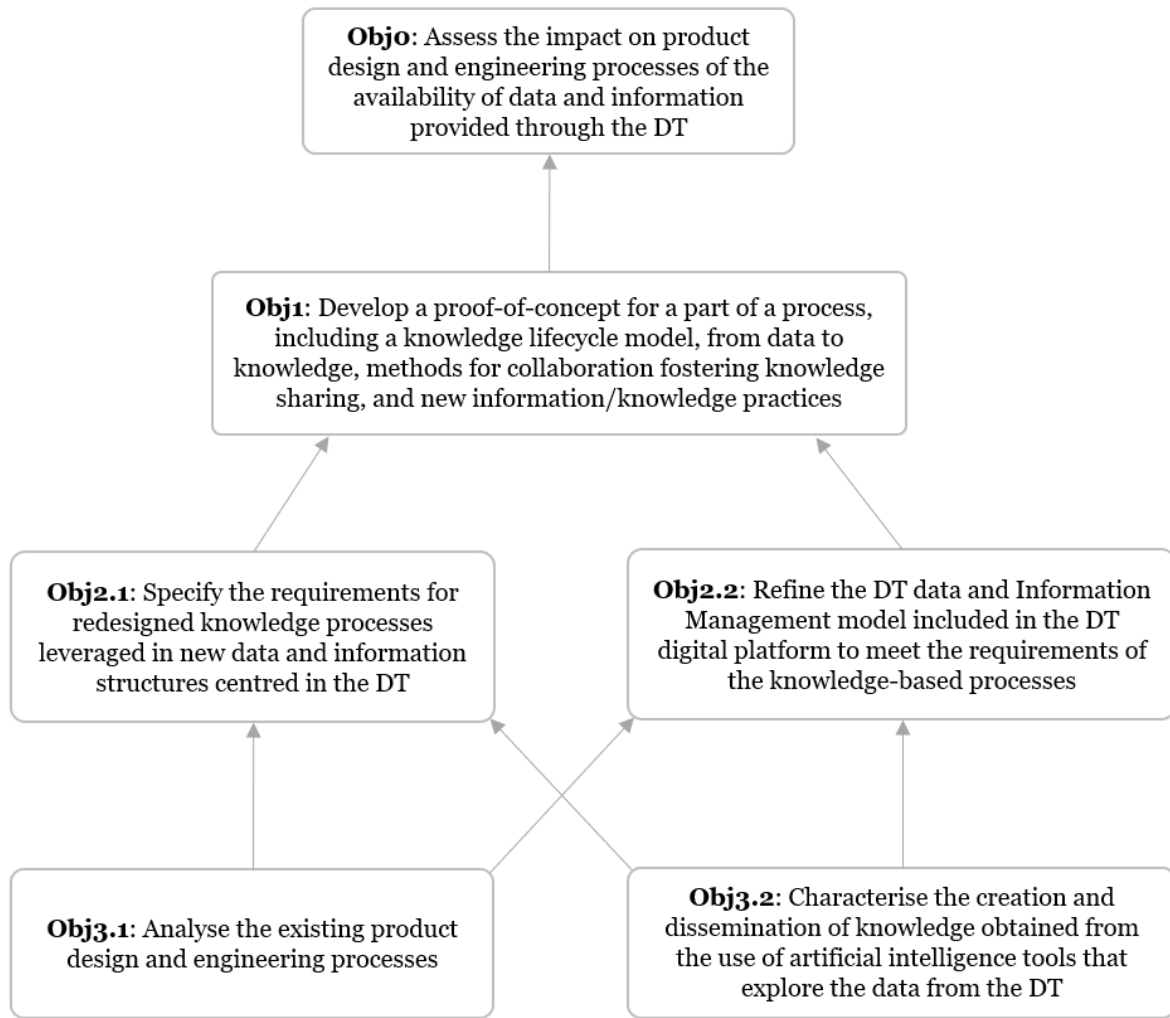


Figure 1 - Objective tree of the dissertation.

1.4. Dissertation structure

This dissertation consists of eight chapters, of which the introduction chapter relates the context and motivation of the research. It presents the problem description, objectives, expected results, and a description of each chapter and topics that are part of the dissertation.

The second chapter regards the literature review, which describes the most relevant works carried out in the academic and professional fields, applying KBE and DT. The first part of the chapter describes the KBE notion, its application and utility in product development, shared characteristics with KM, and implementation methods. The second part of the chapter describes the DT notion, including its initial applications, possible utility in product development, how it relates to KBE and the technologies and methods necessary for its implementation.

The third chapter describes the methodology employed for this dissertation. The first part clarifies why the case study research method was chosen and presents the overall methodology structure for the dissertation. The following section describes the first stages of the TRF4.0 project before the dissertation. The methods and instruments used to collect data from the respondents and participants of the activities that helped support the vision definition and the high-level requirements are detailed. The last section of the chapter describes how the focus group and interviews were prepared and executed and how existing proposals and documents were used to improve engineering processes.

The fourth chapter details the organisation focus of the research, starting with a brief description of Efacec, its history, and market positioning. The following section of the chapter describes the Transformer Business Unit (BU), its departmental organisation, the BU products and services portfolio, and the characterisation of PT from a product perspective. The chapter ends by describing the TRF4.0 project and its objectives.

The fifth chapter presents the research results, starting with the results from the initial two tasks of the project before the dissertation. First, the findings from the vision definition obtained through workshops are presented, and then the findings are related to the description of high-level requirements obtained through workshops and focus groups. The following section of the chapter shows the research findings concerning engineering processes and lifecycle based on the focus group, interviews, and new documents collected during the research. At the end of the chapter, a summary of the results is presented.

The sixth chapter describes the DT concept to PT development identifying key features and capabilities of this emerging technology, followed by analysing current Efacec processes and the PT virtual modelling. The proposition for creating and disseminating knowledge from AI, the requirements for KM and the lifecycle for redesigned knowledge processes, and refinement of the data generated by the DT and IM model with engineering process improvement are detailed. The assessment of the impact on product design and engineering processes from the availability of data and information provided through DT is also evaluated.

The dissertation ends by synthesising the essential findings and providing answers to the research questions. Potential contributions to the area, research limitations and perspectives on DT applicability in product development are also described.

Also included as post-text elements are the bibliographic references consulted to support the theoretical section, the appendices, and annexes that highlight the performed work.

2. Literature review

2.1. Methodology

The methodology adopted to develop the literature review encompasses two main stages. The first stage was related to defining the keywords and the selection of databases, following the querying methods to retrieve the documents. The second stage involved reading and analysing the documents, extracting the findings, and organising the most appropriate information and topics to develop the literature review.

The first stage was interactive since applying the main keywords led to identifying other relevant keywords. This process widened the search scope, whereas it narrowed later in the second stage after a criterion analysis of documents. The selected keywords and employed search conditions are shown in the following tables.

Search conditions for Digital Twin
“Digital Twin”
“Digital Twin” AND “Product Lifecycle Management”
“Digital Twin implementation”
“Digital Twin technologies”
“Digital Twin” AND “Information Management”
“Digital Twin” AND (“product design” OR “product lifecycle”)
“Digital Twin” AND “Knowledge Management”

Table 1 - Keywords and search conditions for DT.

Search conditions for Knowledge-Based Engineering
“Knowledge-Based Engineering”

“Knowledge-Based Engineering” AND (“product design” OR “product lifecycle”)
“Knowledge-Based Engineering” AND “Knowledge Management”

Table 2 - Keywords and search conditions for KBE.

Search conditions for Digital Twin and Knowledge-Based Engineering
“Digital Twin” AND “Knowledge-Based Engineering”

Table 3 - Keywords and search conditions for DT and KBE.

The criteria to select the databases balance quantity and quality offered. The selected databases embrace various subjects, including social, life, medical and computational sciences. As an exception, the Library & Information Science Source database focuses on information science, while the IEEE Xplore database focuses on electronic engineering and computational science subjects.

Databases
Scopus
Science Direct
Library & Information Science Source
IEEE Xplore
Google Scholar

Table 4 - Selected databases.

The second stage involved analysing the retrieved information, including evaluating its structure, ideas, and relevance. Filters used in the selection of the most relevant literature:

- English language;
- Peer-reviewed;

- Published in Q1 and Q2 quartiles journals;
- Published by well-recognised publishers and authors;
- Frequently cited.

The language, peer-review, and citation frequency criteria, in general, can be applied in the filter tools of the databases. A different method was applied when the journal ranking information could not be retrieved from the databases. The information was obtained by searching for a journal on the Scimago Journal & Country Rank website. This process measures the quality of the journal in which the article was published and does not measure the quality of an article.

The documents were retrieved and catalogued in Mendeley Software. Next, a skim-read method was applied to read the abstract, introduction and results, and the most relevant documents were read in-depth to find valuable details about the subject. The most relevant parts of the set are highlighted, commented on, and organised into topics to compose the literature review.

2.2. The notion of Knowledge-Based Engineering

Product development is a sequence of structured processes aiming to deliver new products or improve existing ones. These processes cover distinct areas of organisations and involve activities beginning with the perception of opportunities in the market and ending with the production of the product, sale, and delivery (Ulrich and Eppinger 2012). In addition, these processes run periodically in cycles due to continuous product improvement, mainly in a highly competitive market.

Achieving the goal of improving products implies collecting data from different sources and formats, integrating them, and transforming data into meaningful information for product design improvement. The absence of information about the product, customer, or procedures can lead to revisions in previously completed work, raising the cost and time for the project's development (Chapman and Pinfold 1999).

Computer-Aided Design (CAD) systems enable designers to visualise the virtual representation of an object in a wide variety of ways. Engineers utilise these computer systems to create, analyse, and revise designs, performing these activities using inputs that change virtual geometric components such as component orientation, size, and location. These tools boost the product engineer's efficiency, improve the quality of the design, and simplify the development and storage of documentation resulting from these duties due to their features

(Narayan, Rao, and Sarcar 2008).

Nonetheless, CAD systems are specialised and limited in the geometric manipulation of product representation and generally limited in manipulating information after parametric and function design. For these limitations, it was necessary to develop a way to represent the product design process to provide a precise virtual prototype capable of encompassing all design processes from early development to product evaluation (Calkins, Egging, and Scholz 2000). In sum, a model capable of offering an exact representation of a physical object with geometrical and non-geometrical attributes.

Consequently, KBE systems came into existence at the beginning of the 1980s as a solution for organisational KM, automation, and object reuse. Since then, CAD and KBE tools have started to merge tools and features and, in a unique platform, formalising a new domain of knowledge (Reddy Esanakula, Sridhar, and Rangadu 2015). From the last decade of the twentieth century to the beginning of the twenty-first century, KBE was popularised, and research about the domain was developed, presenting proposals for the concept of KBE. The lack of research and information about the KBE domain before this period can be explained by the fact that this domain has been the exclusive domain of a few highly competitive industries for many years, particularly aerospace and automotive (Rocca 2012).

Different approaches to the KBE concept have been developed by authors (Calkins, Egging, and Scholz 2000). Chapman and Pinfold (1999) argued that KBE is a progression of CAD, integrating these technologies with object-oriented programming and AI. In this context, the goal of the KBE system is to collect information on the processes related to the product and design for automation. According to the authors, the goal is to get the best practices in product design, expert knowledge and experience into an organisational knowledge base (Chapman and Pinfold 1999).

Cooper, Fan and Li (2001) developed a similar characterisation of KBE as a form of a knowledge-based system supported by object-oriented programming and integrated with a geometric modelling tool (Cooper, Fan, and Li 2001). They provided the engineers with a structured and automated approach to product design, reducing the time spent on these tasks. Reddy, Esanakula, Sridhar, and Rangadu (2015) developed a similar view of contextualising operations performance, claiming the primary goal of the KBE approach is to automate recurrent CAD tasks to reduce the cost and time of design or manufacturing (Reddy Esanakula, Sridhar, and Rangadu 2015).

Other authors, notably Bermell-García and Fan (2002), embraced this idea of KBE as integrated CAD software. However, they broaden the application of KBE by stating that KBE

is a Knowledge-Based System that focuses on product engineering design and subsequent activities, such as analysis and manufacturing production planning, cost prediction, and even sales (Bermell-García and Fan 2002).

From 2007 onwards, a new approach emerged related to KBE in professional and scientific literature, aggregating the technology dimension to this domain, and turning KM into a methodology applied to engineering. Ammar-Khodja, Perry, and Bernard (2008) developed the view of KBE as an engineering methodology in charge of storing knowledge about product design and production techniques in models. These models provided relationships between geometric attributes, preserving information about physical features of the product, such as material kinds and functional constraints, information about development processes, and data from external sources like databases (Ammar-Khodja, Perry, and Bernard 2008).

The current and most recent notions refer to KBE as a technology that uses dedicated software tools known as KBE systems to capture and systematically reuse product and process engineering knowledge. Rocca (2012) conceived KBE as a KM approach during product design, which identifies relevant knowledge in an organisation and defines how to capture, formalise, represent, and store it to improve its access, maintenance, and transfer.

In addition, the ultimate goal is to reduce product development time and costs by automating repetitive and non-creative design tasks and supporting multidisciplinary design optimisation in all phases of the design process (Rocca 2012).

The perspective of KBE as a solution for knowledge reuse, which facilitates the development of similar products, is achieved by collecting tacit knowledge from engineers, along with knowledge created and used during the development of the product ("Knowledge Based Engineering (KBE) - CADVision Engineers." 2019). Tacit knowledge is experientially acquired, difficult to articulate and individually owned, playing a vital role in the goal of an individual (Haron 2005).

The current and most recent notions of KBE relate to the objective of KM in capturing and transmitting knowledge to increase organisational performance. Individual and organisational performance can be improved by preserving and utilising the present and future knowledge value of the assets, including human and automated activities (Girard and Girard 2015).

In sum, KBE is the application of KM to manufacturing design and production. Product design and engineering are inherently knowledge-intensive, requiring structures and processes enabling data and IM to facilitate knowledge extraction and sharing among stakeholders. Thereby, there is a trend in associating three topics: KM practices, KBE, and the development of knowledge-based computer software.

2.2.1. KBE project applications and outcomes

The validity and importance of KBE have been shown in projects with high levels of success and several benefits resulting from its adoption. The most notable benefits of installing KBE systems appear to be the reduction in lead time and the reduction in the expenses of product design processes. These benefits are attained through automating procedures that heavily rely on information and knowledge.

Emberey et al. (2007) applied KBE to the design processes of aircraft fuselage panels for the Airbus A380 at Stork Fokker AESP, Papendrecht, The Netherlands, a reduction in lead time. The sub-division process of the prepreg plies, which accounts for approximately 20% of the overall production, was one of the most beneficial activities. From the beginning to the finish of these processes, time was reduced by 75%. Figure 2 shows that within the period needed for ten traditional design cycles, almost 100 designs could be executed using the KBE application (Emberey et al. 2007).

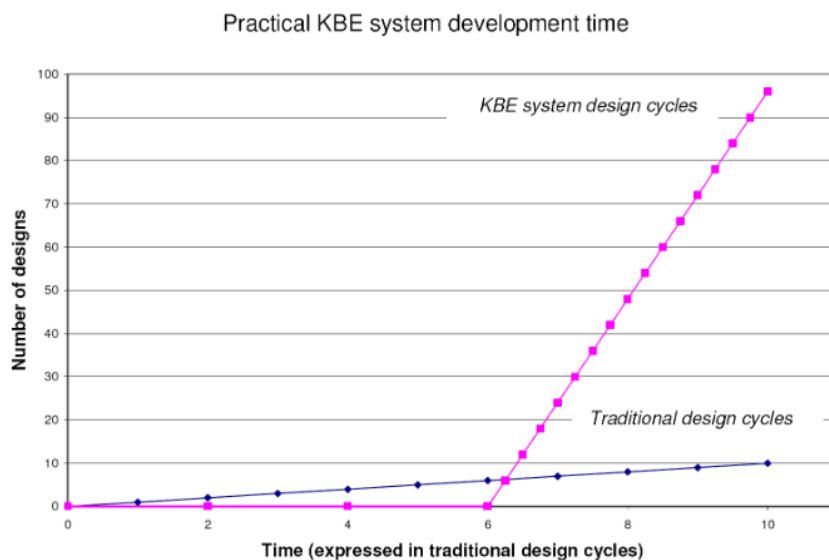


Figure 2 - Time and design cycle comparison between traditional and KBE-enabled design (Emberey et al. 2007).

Lin, Chan, and Wang (2008) implemented another significantly reduced time required to complete product design processes. The authors created a KBE design system for wire drawing matrices in this scenario. It was integrated with pre-existing CAD software, turning matrix-related data into design parameters, geometric operations, and component models. As a result, design time was reduced from 10 days to less than an hour, and costs were drastically reduced. The results also showed that the system could significantly improve design quality while reducing development time and cost (Lin, Chan, and Wang 2008).

In their work, Van Der Elst and Van Tooren (2008) applied the KBE process to create an application that helps designers and manufacturers of aviation wiring harness assign electrical signals to connectors. A time reduction of about 80% was achieved, bringing the repeating time down from many hours to just a few minutes. If the automatic link with the organisational central engineering database were built, further reductions of up to 95% would be possible (Van Der Elst and Van Tooren 2008).

Jaguar created a KBE application that gives significant benefits to the organisation. The feasibility review turned into an interactive task that a Jaguar engineer could finish in minutes rather than a four-week delay. Styling modifications could be made without worrying about the delays that would have occurred if a feasibility review had been performed first. It was possible to quickly examine the possibility of generating the required headlights style to suit the varied legislative requirements for different markets (Cooper, Fan, and Li 2001).

2.2.2. KBE implementation

KBE requires a KM approach that considers various organisational and technical elements, including the industry context, human resources, technological resources, and organisational culture.

According to Zack (1999), this approach balances an organisation's knowledge, resources, and skills with the expertise needed to sell superior products and services to competitors. To achieve the expected results in terms of competitiveness, organisations must strategically analyse their knowledge resources and competencies and broaden their knowledge strategy to fill gaps (Zack 1999).

Consonant to Hansen, Nohria, and Tierney (1999), strategies can be concentrated on technology, particularly implementing reliable Information Systems (IS) through the reusability of coding knowledge. Alternatively, for individuals, the priority is the provision of creative and analytically rigorous recommendations to fix issues using specialised individual knowledge (Hansen, Nohria, and Tierney 1999).

Riege (2005) found three dozen impediments to knowledge sharing and organised under three categories after conducting a comprehensive assessment of overall barriers: (i) organisational barriers, including a lack of transparent rewards and recognition and an encouraging organisational culture; (ii) individual barriers, including fear of running out of time, jeopardising job security, and a lack of trust, among others; and (iii) technological factors, like unsatisfactory Information Technology (IT), lack of technical support and immediate maintenance, and lack of IT training (Riege 2005). In KBE, procedures are frequently used to

guide the knowledge engineer from recognising an issue that KBE can solve to installing software or using a tool that KBE supports.

2.2.3. KBE methodologies

2.2.3.1. MOKA

MOKA (Methodology and tools Oriented to Knowledge-based Applications) is a European research project designed to serve as an international standard for developing KBE systems. MOKA is a widely utilised methodology in the automotive and aerospace sectors that links fundamental knowledge and the KBE platform. Its lifecycle comprises six steps: Identify, Justify, Capture, Formalise, Package and Activate (Reddy Esanakula, Sridhar, and Rangadu 2015).



Figure 3 - Developing lifecycle of KBE according to MOKA (Stokes 2001).

The 6 phases that make up this methodology, as described by Oldham et al. (1998):

- Identify: This is where the type of KBE system is determined if one is required. The conceptual specification of the KBE application is the result of this step. If extra information about the implementation environment is required, identify is also triggered by Activate;
- Justify: This step aims to build a project plan and obtain the approval of decision-making stakeholders at the upper levels of the organisational hierarchy by assessing potential risks such as cultural and technical issues;
- Capture: Using ICARE forms (Illustration, Constraint, Activity, Rules and Entity

forms), basic knowledge is collected and processed into the informal model in this step. Process and hierarchy maps depict the relationships between the ICARE parts;

- Formalise: The formal model is a product of the informal model. MOKA Modelling Language (MML) is based on the Universal Modelling Language (UML);
- Implement: The formal model is implemented into a KBE system;
- Activate: The KBE system is installed, distributed, and supported in this step. If it is determined that more information regarding the implementation environment is required, it may also initiate the Identify phase (Oldham et al. 1998).

Hence, there are two models in the MOKA methodology: formal and informal. The informal model proposes a method for formalising and validating human-understandable knowledge in a model. They also provide a space for knowledge engineers, professionals, and software developers to express their opinions and thoughts.

In contrast, the formal model encapsulates knowledge so that it may be expressed and saved on a computer. This modelling is built-in MML, a UML language that has been tailored to the MOKA technique (Reddy Esanakula, Sridhar, and Rangadu 2015).

The field of the application took place at Stork Fokker AESP in The Netherlands, focusing on the cc panel design. FML is a hybrid material currently being researched for crucial aircraft constructions.

The MOKA was used to create the KBE application in an organised manner. The development lifecycle is based on Stokes's (2001) vision, dividing KM tasks into four categories: identification, capture, storage, and reuse (Stokes 2001).

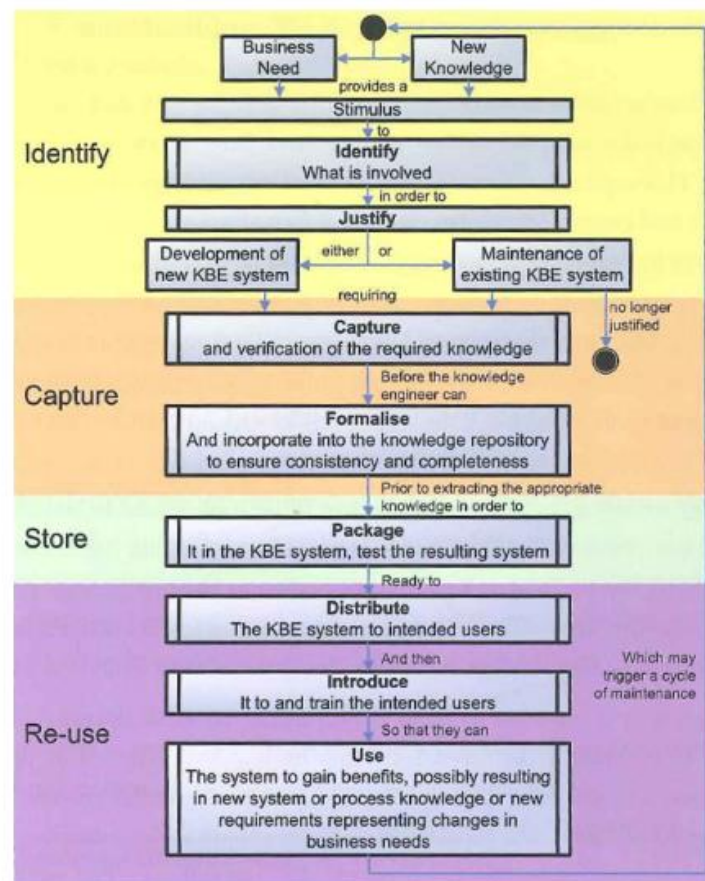


Figure 4 - The KBE development lifecycle according to MOKA (Stokes 2001).

This model facilitates the capture and representation of product and process knowledge, the development and maintenance of the KBE application, and the insertion of engineering data into the models.

Next, the capture phase is divided into extracting, validating and structuring knowledge tasks. The initial and in-depth knowledge extraction was done through interviews and discussions with workers. Following that, inquiries about the techniques utilised evoked tacit knowledge from experts. In this case, a mix of teach-back and focused interviews were used to validate expert knowledge.

The Knowledge Engineering tool PCPACK was used to structure the domain knowledge involved after identifying and justifying the creation of possible KBE applications. PCPACK is a set of seven knowledge tools that work together to enable the acquisition and reuse of information. It integrates ICARE forms to construct informal models of activity diagrams and hierarchical diagrams.

Lastly, CATIA V5 software supports the knowledge storage and reuse phases. CATIA is a

software suite for CAD, Computer-Aided Manufacturing (CAM), Computer-Aided Engineering (CAE), 3D modelling, and PLM (“Design Engineering | CATIA – Dassault Systèmes” 2022). This application uses previously established informal models to automate sections of traditional procedures, resulting in various design alternatives from which the engineer can choose (Emberey et al. 2007).

2.2.3.2. CommonKADS

Another relevant methodology for implementing KBE systems is CommonKADS, the product of a series of international research and application projects on knowledge engineering dating back to 1983.

The CommonKADS idea of the organisation model is to take the relevant elements and experiences from various sources, including organisation theory, business process analysis and IM, to integrate them into a coherent and comprehensive package targeted at knowledge orientation in the organisation (Schreiber et al. 1999).

The knowledge analysis framework is at the core of CommonKADS and provides the tools needed to analyse knowledge-intensive tasks. Predefined reusable knowledge models support the analyst in the modelling process, allow a top-down approach, provide quality control, and handle feasibility assessment. The implementation of CommonKADS aims to answer three questions, which should guide the actions and solutions to be adopted:

- **Why:** It is necessary to ask why is a KM system a potential solution to understand the context and the corporate environment? What benefits, costs, and organisational impacts will it have? What problems should it solve?
- **Which:** Is the purpose of getting the conceptual description of the knowledge used to perform a task. It is necessary to understand the nature and structure of this knowledge and the communication structure used;
- **How:** The focus is on the technical aspects related to the implementation. Therefore, it is necessary to consider how the knowledge should be implemented in the computational system and what is the necessary technological infrastructure to build and run the system.

The answers to these issues are refined into six models that address the organisation, tasks, actors, solution design, and knowledge and its dissemination.

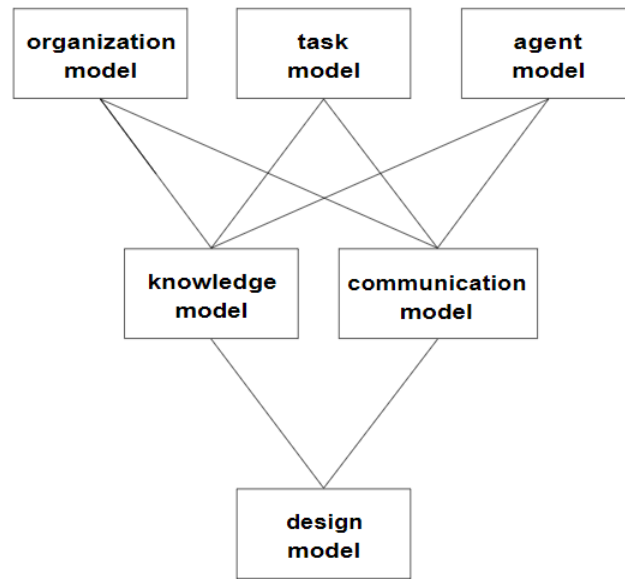


Figure 5 - The CommonKADS model suite with six models (Schreiber et al. 1999).

According to Valentim (2019), the information used to complete these models was gathered through interviews, brainstorming, and documentary research and afterwards recorded in forms. The models, in detail, are presented below:

- Organisation model: Facilitates examining an organisation's significant features to identify challenges and possibilities for knowledge systems, determine their viability, and analyse the effects of desired knowledge actions on the organisation;
- Task model: Tasks are the relevant components of a business process. The model examines the overall layout of the task, inputs and outputs, preconditions, performance standards, and required resources and competencies;
- Agent model: Agents are task executors. The agent model explains the features of agents, including their skills, authorisation to act, and constraints. A human, IS, or any other creature capable of performing a task can be considered agents;
- Knowledge model: The goal is to describe the different types and structures of knowledge used to complete a task. It gives a human-understandable, implementation-independent description of the function of different knowledge components in problem-solving;
- Communication model: Since multiple agents may be participating in a task, it is critical to model their communication interactions. As with the knowledge model, the

communication model accomplishes this in a conceptual and implementation-independent way;

- Design model: The design model specifies the technical system architecture, implementation platform, software modules, representational constructs, and computational methods required to implement the functions of knowledge and communication models (Valentim 2019).

The KBE system has two applications:

- Software development;
- Knowledge analysis and modelling.

A programmer oversees the first, while a knowledge engineer is responsible for the second. In both circumstances, the project manager oversees this work.

The knowledge engineer gathers information from experts and users and then passes it on to the programmer to implement it in the software. After the programmer's work is completed, the developed system is validated by specialists (Schreiber et al. 1999).

2.2.3.3. Other methodologies

KOMPRESSA (Knowledge-Oriented Approach for the Planning and Rapid Engineering of Small-Scale Applications) is another available KBE methodology (Lovett, Ingram, and Bancroft 2000). It focuses on assisting the KBE implementation in Small and Medium Enterprises (SMEs). It contains principles, instructions, formats, strategies, and recommendations for complex knowledge analysis, design, modelling, implementation, and documentation. It is well renowned for its versatility in application and covers the lifetime development of KBE by maximising customer involvement based on expertise (Reddy Esanakula, Sridhar, and Rangadu 2015).

KNOMAD (Knowledge Nurture for Optimal Multidisciplinary Analysis and Design) was created for the analytical use of multidisciplinary knowledge in design and manufacturing. KNOMAD has integrated knowledge representation with the design process to increase knowledge retention and application maintenance with the end-user role (Curran et al. 2010).

DEE (Design and Engineering Engine), another KBE methodology, is a multidisciplinary design optimisation strategy. The Design Process Optimisation module, the Multi-Model Generator (MMG) module, and the Detailed Analysis module make up DEE. The DEE methodology is superior to the MOKA approach because it involves extensive discipline analysis and multidisciplinary optimisation methodologies. On the other hand, DEE does not

include a methodical, codified approach to capturing, formalising, and integrating information into business processes (Curran et al. 2010).

Another KBE approach takes advantage of ontologies, sets of concepts, and their relationships within a domain to capture and reuse knowledge. Baumeister, Reutelshoefer, and Puppe (2011) adopted this approach in implementing a semantic wiki as a collaborative tool to help decision-making. In this case, ontologies are used to classify each wiki article and relate concepts within them. This strategy creates a knowledge base on this wiki platform, helping employees share or find solutions to a given problem (Baumeister, Reutelshoefer, and Puppe 2011).

The application of online platforms was another approach developed by Kulon, Broomhead, and Mynors (2006). This method developed a KBE system using a web platform that integrates the hot forging die design process into a single framework and guides the user through the design process. Further, it allowed for generating forgeable geometry from a component profile while considering machine, material, and forging organisation-specific data and design considerations (Kulon, Broomhead, and Mynors 2006).

2.3. The notion of the Digital Twin

The DT concept emerged and was first introduced in 2002 by Michael Grieves at the University of Michigan through Grieves' Executive Course on PLM (Mayani, Svendsen, and Oedegaard 2018). Grieves and Vickers (2017) defined DT as a PLM application that includes a physical system and a virtual twin containing all the information related to this physical system (Grieves and Vickers 2017).

Still, in 2002, a preliminary version of the DT was suggested that included three components, a physical product, a virtual product, and their connections (Fei Tao, Zhang, et al. 2019).

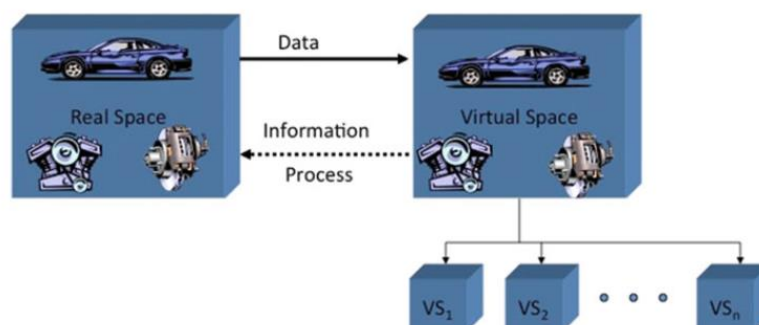


Figure 6 - Conceptual ideal for PLM. Dr. Michael Grieves, University of Michigan, Lurie Engineering Center, Dec 3, 2002.

The first journal publication on how DTs could be used to forecast the structural life of

aeroplanes was published in 2011 (E. J. Tuegel et al. 2011). The National Aeronautics and Space Administration (NASA) brought back the concept of DTs in 2012, defining it as a multiphysics, multiscale, probabilistic, ultra-fidelity simulation. It should reflect the state of a corresponding twin on a timely basis based on historical data, real-time sensor data, and a physical model (Glaessgen and Stargel 2012). In the following years, new concepts and understandings of DT emerged due to research and professional work expansion coordinated with technology evolution.

Some authors believed that the DT research should focus on simulation. In their work, Weyer et al. (2016) described the convergence of the physical world with its digital equivalent, where the latter must closely mirror the former, resulting in an unprecedented volume of data that the factory's digital representation must handle. The virtual world must follow the physical world in real-time based on previously widely accepted digital representation. The DT may monitor, modify, and optimise actual operations, predict failures, and enhance efficiency (Weyer et al. 2016).

INDIVIDUAL APPLICATION	SIMULATION TOOLS	SIMULATION-BASED SYSTEM DESIGN	DIGITAL TWIN CONCEPT
			Simulation is a core functionality of systems by means of seamless assistance along the entire life cycle, e.g. supporting operation and service with direct linkage to operation data
Simulation is limited to very specific topics by experts, e.g. mechanics	Simulation is a standard tool to answer specific design and engineering questions, e.g. fluid dynamics	Simulation allows a systemic approach to multi-level and – disciplinary systems with enhanced range of applications, e.g. model based system engineering	
1960+	1985+	2000+	2016+

Figure 7 - Waves and simulation as core functionality for DT (Weyer et al. 2016).

Following this view, Gabor et al. (2016) characterised the ability of DTs to precisely simulate events on many scales of space and time and distinguish them. They may do so not only because they are based on specialist knowledge, such as an advanced physics simulation, but also because they can collect data from all deployed systems of their sort and aggregate the experience gained in the field. One of the most challenging tasks is fine-tuning the performance of the simulation software so that events in the DT can be recreated considerably faster than in the real world (Gabor et al. 2016).

Some researchers believe that the DT should have three dimensions: physical, virtual, and connection sections, with the virtual space being translated to the physical space via the connection component, which transfers data and information. Grieves (2014) proposes a DT

concept model divided into three parts:

- Physical items in real space;
- Virtual products in virtual space;
- Data and information connections integrate virtual and physical products (Grieves 2014).

One approach was to create a unified repository that would link the virtual and physical assets together to deliver the substantial benefits of this connection. The unified repository would be populated by virtual development tools and physical collecting tools. This method would allow virtual and physical products to communicate in both directions (Grieves 2014).

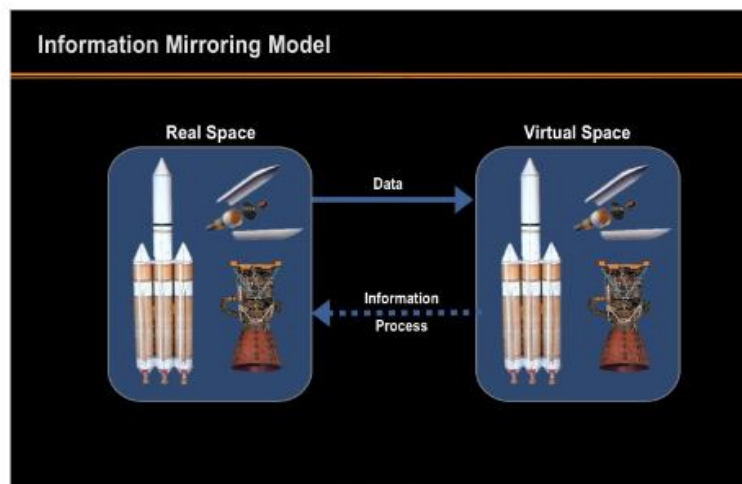


Figure 8 - The three-dimension model for the DT (Gabor et al. 2016).

The approach was used by Qi and Tao (2018), arguing that Big Data is a critical part of the DT, representing the connections that integrate the virtual and physical products. Without Big Data, most of the functions of DT would be impractical, and without DT, the Big Data analysis and the actual manufacturing process would not be coupled and integrated (Qi and Tao 2018).

“Big data is a term that describes large volumes of high velocity, complex and variable data that require advanced techniques and technologies to enable the capture, storage, distribution, management, and analysis of the information” (TechAmerica Foundation’s Federal Big Data Commission 2012).

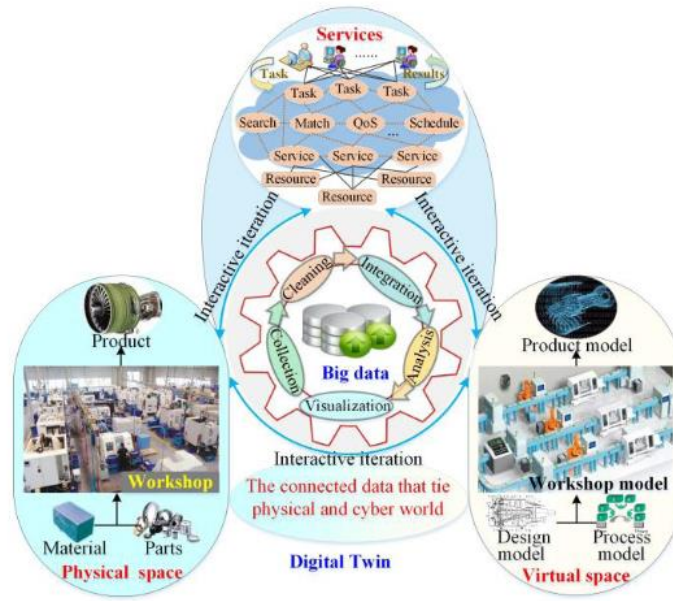


Figure 9 - The fusion of DT, Big Data and services in manufacturing, representing the three-dimension model (Qi and Tao 2018).

Tao and Zhang (2017) work proposed that a complete DT would contain five dimensions: physical part, virtual part, connection, data, and service, based on the three-dimension model for the DT. For DTs, all five dimensions are equally crucial. The virtual part supports the simulation of the physical part, decision-making, and control. Data is at the heart of DTs since it is required to create new knowledge. Furthermore, DTs lead to new services that improve the convenience of an engineering system, reliability, and productivity. Finally, the connecting part bridges the physical, virtual, data, and service components (Tao and Zhang 2017).

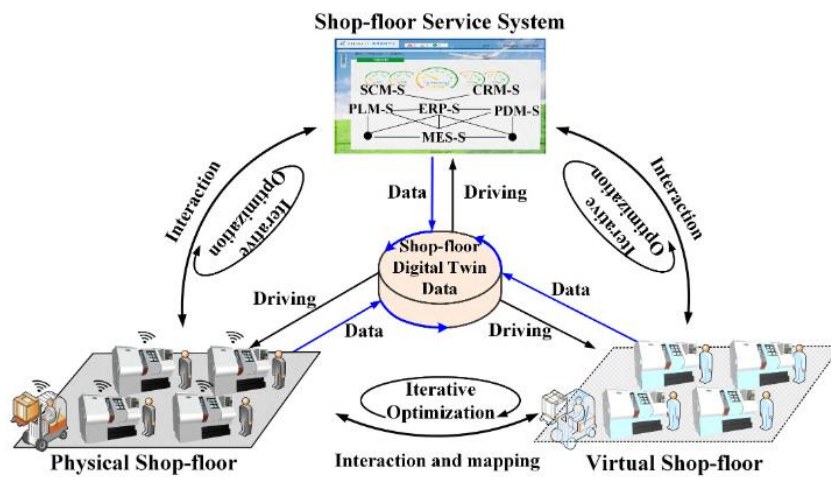


Figure 10 - Five-dimension model for the DT (Tao and Zhang 2017).

Information science, production engineering, data science, and computer science all contribute to the theoretical foundations of DTs. Despite the points of view, it indicates that the DT has a set of features and functionalities generally acknowledged in the literature as inherent to its technology. One of these is its connection to a physical element, concluding that a DT cannot exist without being related to one or more physical components. Furthermore, simulation is considered a feature intrinsically linked to the DT. Most authors refer to this link as being made through the transmission of data and information.

The most recent concept of DT emerged from C. Zhuang, Liu, and Xiong (2018), which defined DT as a virtual, dynamic model in the virtual world that is entirely consistent with its corresponding physical entity in the real world and can simulate the characteristics of the physical counterpart, behaviour, life and performance in a timely fashion (Zhuang, Liu, and Xiong 2018). Moreover, F. Tao et al. (2018) defined DTs as virtual models of physical objects created digitally to simulate their behaviours in real-world environments (F. Tao et al. 2018). In sum, the DT is the digital counterpart of the physical product that aggregates real-time and historical data and information about the product. Furthermore, historical data in this context means that the whole lifecycle of the product is covered.

2.3.1. Data Twin project applications and outcomes

NASA was one of the first organisations to investigate the possibility of incorporating DT into organisational processes, and it focuses on the architectural difficulties of distributed, heterogeneous, and long-lived mission systems. NASA can see and understand how systems might perform early in their lifecycles through simulation, without the danger or expense of needing to build and transfer the system to the proper environment. It also enables NASA to examine current massive, sophisticated, expensive, or dangerous systems without possessing the physical system.

Some of the significant benefits of high-fidelity modelling and simulation, supported by high-performance computing and information processing, include creative problem solving; experimentation; what-if analysis; insight into constraints and causality; large-scale data analysis and integration, high-reliability real-time control; lower lifecycle cost, among others. The DT continuously forecasts the health of the vehicle/system, the Remaining Useful Life (RUL), and the probability of mission success by integrating all available data (Shafto et al. 2010).

A similar application was proposed by the United States Air Force, giving rise to a specific term called Airframe Digital Twin (ADT). The ADT implementation could be possible because of advances in high-performance computing and the ability to reduce the model's uncertainty.

The dimensions of the structure, the status of the materials that make it up throughout its history, the repairs and alterations made during service, and other data like temperature and forces applied to the aircraft are captured by ADT.

The ADT acts as a virtual health sensor through data set processing and estimates future maintenance needs for an individual aircraft using computational simulations. Calculations are also done to anticipate the aircraft's ability to accomplish the mission's criteria (E. Tuegel 2012).

2.3.2. Digital Twin's potential features in the product lifecycle

The implementation of DT in product design is yet in its early stages of research. However, various authors have already written about its potential utility at various product lifecycle stages. DT allows for the integration of information and physical product models and their iterative optimisation, resulting in a shorter design cycle and lower rework costs (Li et al. 2019).

Barricelli, Casiraghi, and Fogli (2019) described two possible lifecycles for DTs, from their design to their dismissal. The first situation is one in which the object that has to be twinned does not yet exist; in this situation, the design process simultaneously creates the object and its DT. The second is about an object that already exists but has no DT; in this case, the design process focuses on extending the objects to make it.

Both lifecycles share the same timeline: a first design phase, a development phase, an operational phase, and finally, a dismissal phase. To describe these two lifecycles, a running example of a medical device, i.e., a computer tomography scanner, was used (Barricelli, Casiraghi, and Fogli 2019).

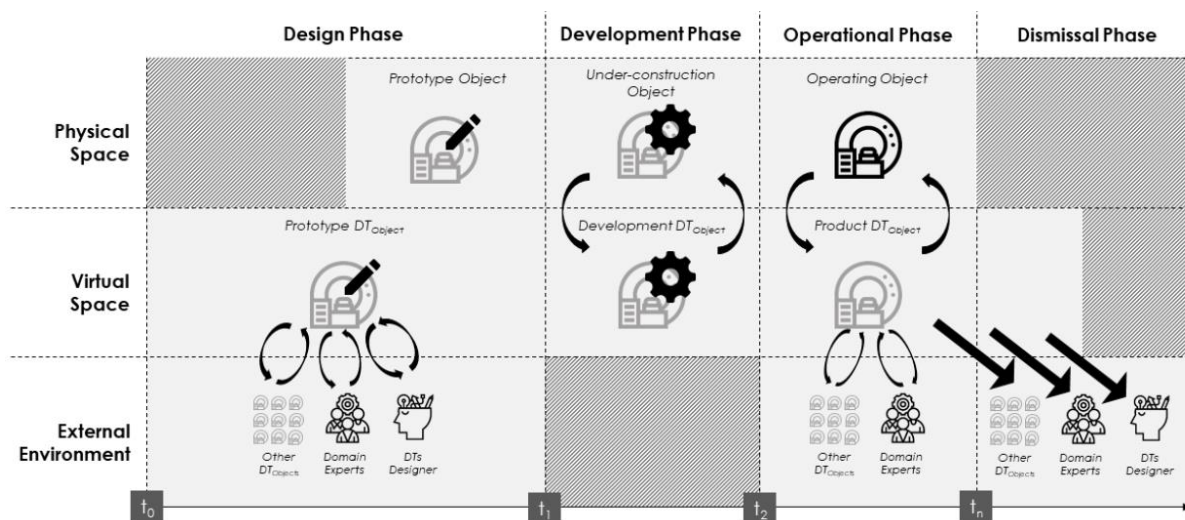


Figure 11 - The lifecycle of a computer tomography scanner and its DT, from design to dismissal (Barricelli, Casiraghi, and Fogli 2019).

A product's lifecycle can be defined as a series of steps through which a product moves from design, production, and use to disposal. It can be divided into three main stages: Beginning-Of-Life (BOL), which includes the design and manufacturing stages, Middle-Of-Life (MOL), which includes the use, service and maintenance stages and End-Of-Life (EOL), where products are collected, disassembled, remanufactured, recycled, reused or discarded (Kiritsis, Bufardi, and Xirouchakis 2003).

Riedelsheimer, Dorfhuber, and Stark (2020) described a project employing the DT concept focused on sustainability in the clothing industry and developed a lifecycle strategy. For the lifecycle phases BOL, MOL and EOL, user stories were created to describe the purchase, repair and care as well as reselling and recycling phases. Each user story comprises the user's activities, mindset and role (Riedelsheimer, Dorfhuber, and Stark 2020).

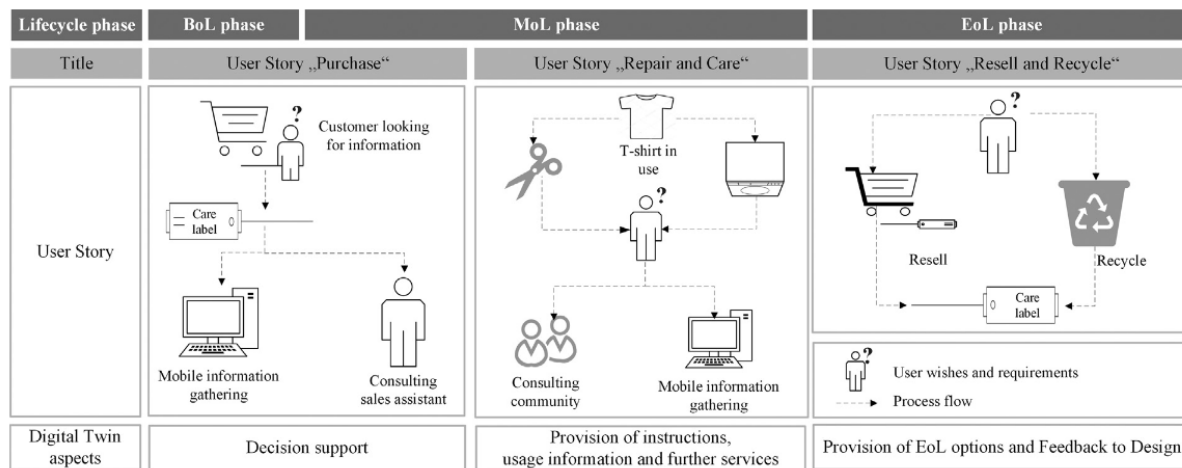


Figure 12 - User Stories with requirements and desires in each lifecycle phase (Riedelsheimer, Dorfhuber, and Stark 2020).

2.3.2.1. Application in the design phase

Canedo (2016) identified DTs as a new way to manage IoT and claimed that incorporating data feedback from the DTs and feedforward flows will improve product design. Furthermore, DT is a mechanism for managing IoT devices and System of Systems (SoS) across their lifecycle (Canedo 2016). Zhuang et al. (2017) investigated how DTs are used in product design and proposed some ideas and techniques for implementing design-oriented (Zhuang et al. 2017).

Yu et al. (2017) suggested a new DT mode to manage 3D product configuration. They claimed that using DTs in design could help to improve communication and synchronisation between design and manufacturing (Yu et al. 2017). Zhang et al. (2017) developed a DT-based technique

to design manufacturing lines. The approach was validated through a case study on a glass production line (Zhang et al. 2017).

Schleich et al. (2017) proposed a novel DT model for geometrical variations management. The aim of managing geometric variations is to ensure that the required geometric attributes of the product are met despite the presence of geometric deviations of the part. They claimed that the DT enabled designers to assess a product's quality from the early stages of design, when simple product models are used to decide on product concepts, to detail design, where sophisticated simulation models support the dimensioning and design of parts and subassemblies. The DT is beneficial not only for representation but also for predicting expected product behaviour. Indeed, it is asserted that using a DT verifies product adherence to standards (Schleich et al. 2017).

Fei Tao, Sui, et al. (2019) developed a DT-driven design framework because most design decisions were made without proper interactions among the expected, interpreted, and external spaces. They saw several potential DT uses in product planning, conceptual design, and detailed design, among other design phases. A case study on bicycle design was undertaken to establish the foundation for collecting and analysing massive amounts of bicycle data. These data would aid in creating a DT for bicycles and assist designers in developing bicycles (Fei Tao, Sui, et al. 2019).

Howard (2019) discussed how a DT might help virtual hardware validation produce optimal designs, reduce cost and money, and accelerate development, validation, and manufacturing release. Since physical development will be impractical in the future, virtual validation will be essential to bring products to market (Howard 2019). Xiao et al. (2019) described a solid rocket motor DT to shift from a typical experience-based and semi-experience-based design mode to a data-driven and model-driven design mode (Xiao et al. 2019).

2.3.2.2. Application in the manufacturing phase

Physical and digital interaction in closed-loop manufacturing is required in modern manufacturing. Elements become context-conscious through communication with their environment and can make intelligent decisions without being explicitly programmed. DT is the critical enabling factor towards this vision.

Manufacturing has traditionally been defined as an industrial process that converts raw resources into finished commodities. It is shifting from primary to innovative processes due to increased demand for product quality and faster market reaction (Esmaeilian, Behdad, and S. Wang 2016).

In this context, smart manufacturing is one of the strategic focuses of all significant manufacturing efforts, such as Industry 4.0 (Fei Tao, Zhang, et al. 2019). In closed-loop manufacturing, physical and digital contact is essential, and the crucial role of DT is to make the physical and virtual worlds communicate and interact.

Grieves (2014) envisioned applications of the DT in his work. It is feasible to recreate the product's manufacturing environment, encompassing most automated and manual procedures that make up the manufacturing process. Assembly, robotic welding, shaping, milling, and other factory floor operations are among them, and finally, collaborating with others to keep up-to-date on the things generated is essential (Grieves 2014).

Rosen et al. (2015) demonstrated how DT was used to transform a cyber-physical manufacturing system into an autonomous system. Autonomous systems are intelligent devices carrying high-level tasks without detailed programming or human control. They know their abilities and status and may choose between several actions and coordinate and execute skills. Autonomous systems will require access to highly realistic representations of the current state of the process and their behaviour in real-world interactions with their environment, often a DT (Rosen et al. 2015).

Fei Tao and Zhang (2017) investigated the physical shop-floor, virtual shop-floor, shop-floor service system, and shop-floor DT data as part of a revolutionary DT shop-floor idea. The DT combined data from physical assets and digital models to produce helpful production information (F. Tao and Zhang 2017).

Konstantinov et al. (2017) explored how DTs may help with production optimisation, converting current tools to support DTs, and adopting the vueOne, a set of virtual engineering tools to optimise the insertion of the magnet into a rotor (Konstantinov et al. 2017).

Park et al. (2019) created and implemented a DT to address issues of personalised manufacturing and distributed manufacturing systems. The DT was developed to track historical data, monitor the present in real-time, and aid future operational decision-making (Park et al. 2019).

2.3.2.3. Application in the service phase

Manufacturers and suppliers typically decentralise and lose track of products throughout the service phase. As a result, managing and gaining access to their data and realising a closed-loop data stream is difficult. Furthermore, while the existing virtual model may be a good depiction of the product's design, it has no connection to a specific manufactured part (Anderl et al. 2018).

Moreover, whereas a produced part is unrelated to the final product, items from the same batch may operate differently under different service conditions. Users are primarily concerned with the dependability and convenience of the product. On the other hand, manufacturers and suppliers are primarily concerned with real-time product operation status, maintenance methods, and so on (Liu et al. 2021). Thinking about the solution to these problems, some leading organisations have applied DTs in the service phase in aerospace engineering, electric grid, car manufacturing, petroleum industry, and healthcare, among others.

E. J. Tuegel et al. (2011) proposed an aircraft structural life prediction method based on an ultra-high-fidelity aircraft model through a DT. A reasonable estimate for the flight path of the mission and manoeuvres was established (E. J. Tuegel et al. 2011).

General Electric demonstrated that the DT might shift how wind farms are built, operated, and maintained. The new paradigm can boost operating efficiency by 20% compared to the previous one without DTs. GE also created the technology and software needed to set up the DT windfarm (GE Renewable Energy 2016).

Tesla Inc. aims to create a DT for each car it produces, enabling synchronous data flow between the vehicle and the plant. Simultaneously, other businesses rely on complicated product models to improve virtual and augmented reality immersion (Schleich et al. 2017).

Siemens utilised DTs in the power system and the wastewater treatment plant. It created the DT to plan, operate, and maintain a power system in Finland, resulting in significant improvements in automation, data use, and decision-making. Siemens also created a DT for a wastewater treatment facility to monitor pipes in real-time, save energy, and predict failure tendencies ahead of time (Fei Tao, Zhang, and Nee 2019) (Huxoll et al. 2021).

2.3.2.4. Application in the after-service phase

The approach to managing the after-service stage in DT is still developing in the literature. The project developed by Riedelsheimer, Dorfhuber, and Stark (2020) detailed a strategy for the EOL stage. An application created for the project recommends recycling, reselling, or reusing based on data gathered throughout the lifecycle. As a result, there is potential to reduce energy and detergent usage through the service provided by the application (Riedelsheimer, Dorfhuber, and Stark 2020).

Barricelli, Casiraghi, and Fogli (2019), in their work where lifecycles of a medical device were described, a strategy for the EOL phase was also detailed. When the object stops being used due to obsolescence or any other reason, it must be disassembled, and the dismissal phase begins, first for the physical object and then for the DT object. The stored historical data of the

Product DT object are backed up and made available to other DT objects and domain experts. In this way, designers, or any other domain expert, will be able to use the collected information to optimise the production of future devices (Barricelli, Casiraghi, and Fogli 2019).

2.3.3. Emerging topics

2.3.3.1. The Cognitive Digital Twin

Cognitive power is required to reach a higher level of automation and intelligence, discern complicated and unpredictable behaviours, and develop dynamic approaches autonomously. In recent years, there has been a movement to combine DT with sophisticated semantic modelling technologies to give DT cognition capabilities. In several recent investigations, a new notion called Cognitive Digital Twin (CDT), or Cognitive Twin (CT) in some situations, has emerged as a promising evolution trend of DT.

Lu et al. (2020) suggested a formal description of CTs as DTs with increased semantic capabilities for detecting the dynamics of virtual model evolution, facilitating the understanding of virtual model inter-relationships, and improving decision-making (Lu et al. 2020). Their study developed a framework based on a knowledge graph to aid in developing CDTs and their application. Furthermore, a toolchain was created to enable different components of the CDT models, consisting of multiple existing applications and platforms. The suggested CDTs framework and related toolchains were verified through an application case to assist IoT system development decision-making.

The most potential enabler for achieving the CDT vision is the knowledge graph. It describes the topology of structured and unstructured data using a graph model of nodes and edges, allowing for formal, semantic, and structured knowledge representation (Nguyen, Vu, and Jung 2020).

Based on existing CDT definitions from other authors and the identified key features, Zheng, Lu, and Kiritsis (2021) also proposed the following definition of CDT: a digital representation of a physical system that is augmented with specific cognitive capabilities and support to execute autonomous activities; consists of a set of semantically interconnected digital models related to different lifecycle phases of the physical system, including its subsystems and components; and evolves continuously (Zheng, Lu, and Kiritsis 2021).

Moreover, their work argues that the CDT concept is based on DT and should include all essential characteristics of the DT, such as digital representations of physical systems, implying that they both contain the three essential elements: physical entities in real space; virtual entities in virtual space; and connections between physical and virtual entities. Furthermore,

the virtual entities of both DT and CDT can communicate with their physical counterparts and dynamically update them (Zheng, Lu, and Kiritsis 2021).

It is essential to note that the CDT notion is not intended to take on the role of DT. Instead, it is a more integrated and expanded version of the current DT paradigm. As a result, all CDTs are specific types of DTs with additional features, including cognitive capacities, cross-lifecycle phases, and numerous system levels. Their structural complexity and cognitive capability are the most significant differences between them.

A CDT is usually more sophisticated than a DT in terms of architecture and the number of lifecycle phases involved. Most DTs are dedicated to a specific system, product, subsystem, component, or another aspect of the lifecycle. On the other hand, a CDT should have various digital models corresponding to distinct subsystems and components of a complex system and multiple lifecycle stages.

From the perspective of lifecycle phases and system hierarchy levels, this viewpoint demonstrates how digital models are identified concerning system hierarchy levels and lifecycle stages.

A sophisticated system is considered an SoS, which comprises multiple systems. Each system comprises several subsystems, each of which can be further broken down into a set of components and each component into multiple sections. Each element corresponds to one or more dynamic and developing digital models.

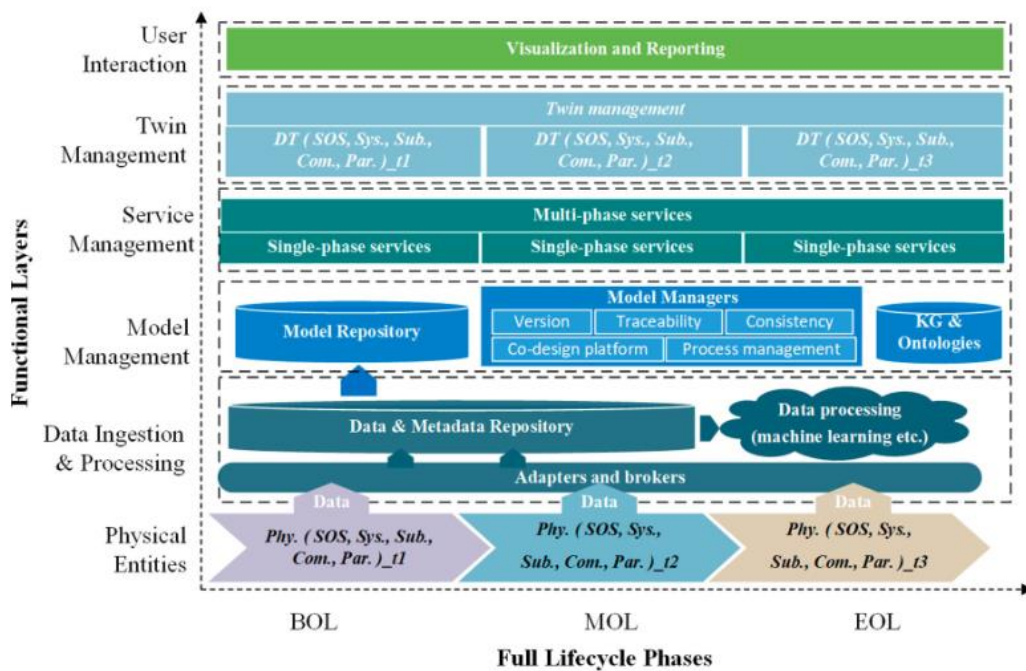


Figure 13 - CDT functional architecture layers and lifecycle stages plane (Zheng, Lu, and Kiritsis 2021).

According to a review of related work, the CDT is still in its early stages. Previous research has attempted to use sophisticated technology to extend existing DT models from diverse viewpoints. CDT has yet to be broadly deployed and confirmed as an emerging idea in the industry. Most published studies either look at the theoretical aspects of CDT or concentrate on the CDT vision. On the other hand, several ongoing studies and projects aim to test the CDT's viability by applying it to various industry contexts.

2.3.3.2. Digital Twin and Blockchain

The literature review shows few studies concerning Data Management (DM), including data storage, access, sharing, and authenticity, which should be executed securely and efficiently. Among the problems that can be mentioned is the overwritten status of virtual products, ideally instantaneously to match the latest state of the physical counterpart, which means the loss of historical data.

Huang et al. (2020) proposed an approach to solving the DM problems of DT within the product lifecycle, a DM method based on Blockchain technology. A case study involving the DT of a turbine demonstrates the efficacy of the suggested DM method. The results show that the proposed method can simultaneously solve DM problems (Huang et al. 2020).

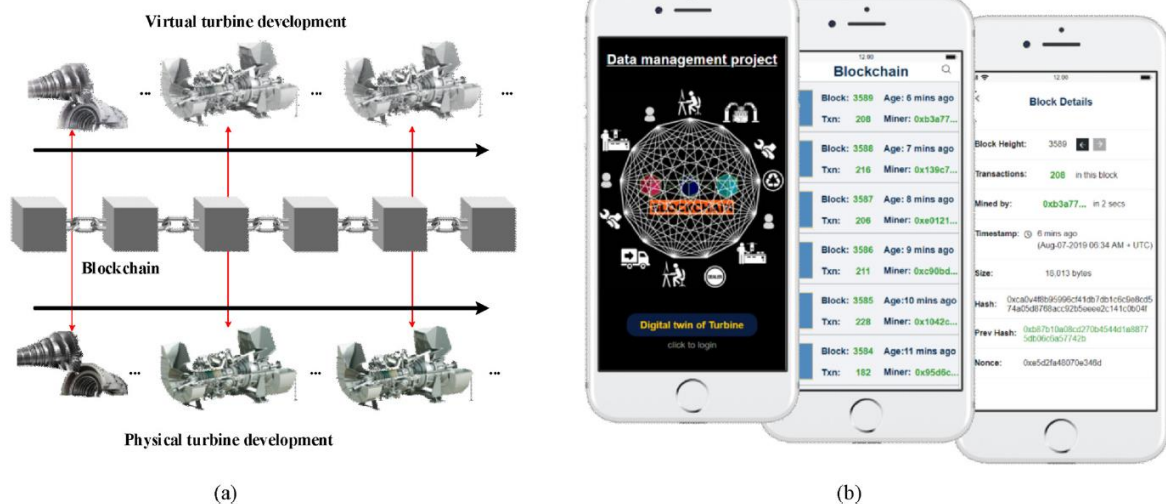


Figure 14 - (a) The Blockchain utilised to record the data of DT of the turbine; (b) DM platform for DT of the turbine (Huang et al. 2020).

Nakamoto (2008) conceived Blockchain, proposing a peer-to-peer network using proof-of-

work to record a public history of transactions, storing data so that changing, hacking, or cheating the system is difficult or impossible (Nakamoto 2008).

Namely, data can be stored in blocks, data access should be verified, data sharing is efficient through peer-to-peer networks, and data authenticity can be guaranteed through traceability to prevent data overwriting.

Otherwise, because the entire product lifecycle data is stored on the Blockchain, it is essential to query it directly to retrieve the DT data at a certain period. The documents stored in the Blockchain will reduce the Blockchain's query efficiency, which is undesirable for DT's DM. It is a bottleneck that should be treated in future academic works.

Mandolla et al. (2019) focused on the stages that characterise the metal Additive Manufacturing (AM) process, which can be used to build a component for the aircraft sector and suggested a DT for AM in the aircraft industry using Blockchain technology. The article offers a hypothetical solution for safeguarding and organising data created by an end-to-end AM process in the aerospace sector and demonstrates how Blockchain-based organisations might create secure and linked manufacturing infrastructure (Mandolla et al. 2019).

In recent years, authors considered the potential value of Blockchain technology in manufacturing and engineering. Kasten (2020) found 90 manufacturing and 20 engineering applications of Blockchain (Kasten 2020). The application of Blockchain in manufacturing and engineering is still in its early stages. Several ongoing studies aim to put the Blockchain to the test by applying it to various industry scenarios.

A DT is built out of data input from IoT sensors on the actual equipment, and security is a significant concern with IoT that has slowed its large-scale adoption. IoT devices often suffer from security vulnerabilities that make them an easy target for Distributed Denial of Service (DDoS) attacks from cyber-criminals (Snehi and Bhandari 2021).

In DDoS attacks, multiple compromised computer systems bombard a target, such as a central server, with a massive volume of simultaneous data requests, thereby causing a denial of service for users of the targeted system. Several DDoS attacks in recent years have disrupted organisations and individuals (Hoque, Bhattacharyya, and Kalita 2015).

Another matter with current IoT networks is scalability. As the number of devices connected through an IoT network increases, current centralised systems to authenticate, authorise and connect other network nodes will become bottlenecks. Getting around this barrier would necessitate enormous investments into servers handling a large amount of information exchange, and the entire network could go down if the server becomes inaccessible (Shwe, Jet,

and Chong 2016).

Blockchain, as a distributed and secure ledger, records all transactions into a hierarchically expanding chain of blocks. Edge computing brings cloud capabilities closer to computation tasks, so the convergence of Blockchain with edge computing paradigms can overcome security and scalability issues (Wu, Dai, and Wang 2021).

2.3.3.3. Digital Twin and Socio-Technical Systems Design

Socio-Technical Systems Design (STS-D) is a field that investigates how Socio-Technical systems concepts can be applied to the design process. The Traditional STS-D goal, as stated by Pasmore et al. (2019), was defined to “*design the social system around a fixed technical system in a way that maximised throughput and quality while satisfying human needs*” (Pasmore et al. 2019).

The design and development of DTs are frequently explored from a technical perspective. Organisations developing DT frequently limit the social aspect to rethinking how stakeholders interact and communicate rather than approaching DT design from a Socio-Technical systems perspective (Rebentisch et al. 2021).

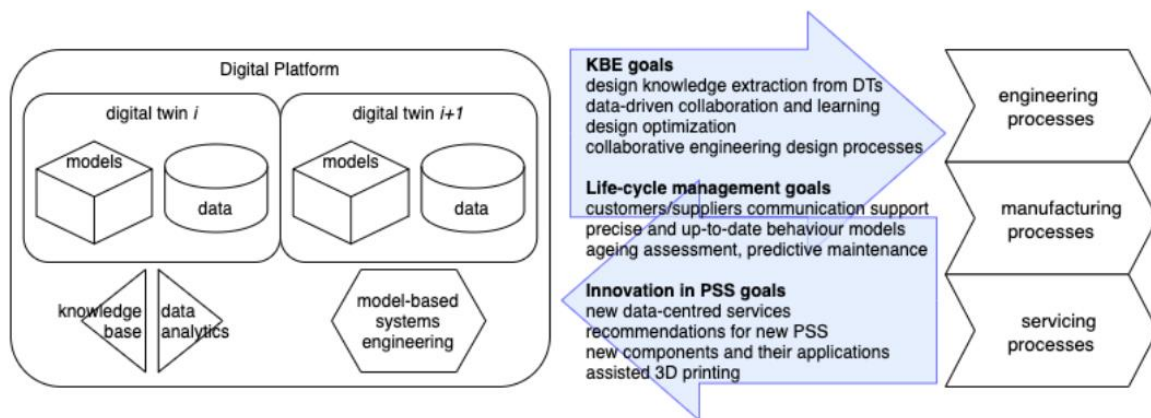


Figure 15 - Strategic goals driving the STS-D (Rebentisch et al. 2021).

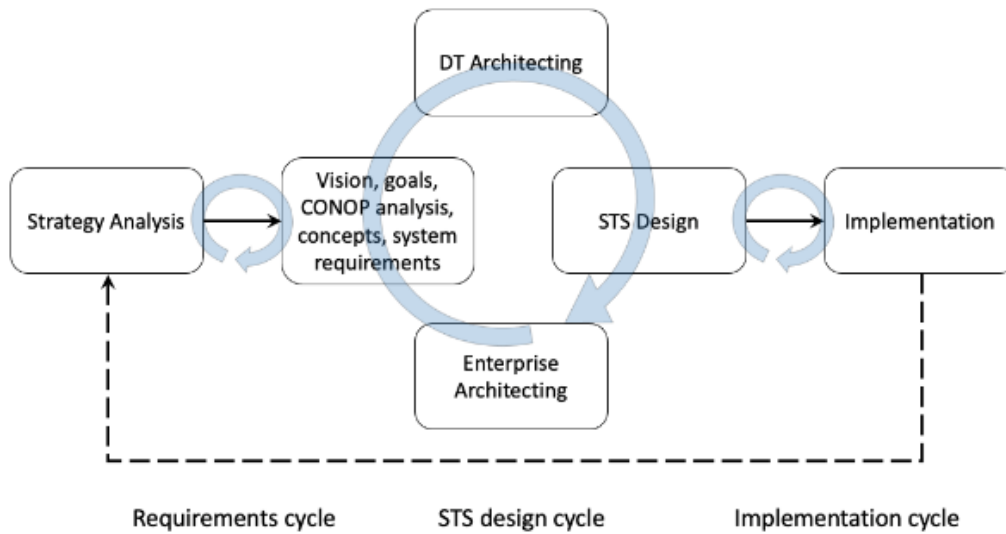


Figure 16 - Socio-Technical System Analysis Framework for DTs (Rebentisch et al. 2021).

The authors claimed that this approach could enable DT implementation outcomes to be better aligned with the organisation's strategic goals and objectives and help clarify what the DT can and should do for the organisation.

2.4. Knowledge-Based Engineering and Digital Twin

Considering the features proposed for the DT during a product's lifecycle, there appears to be a possible complementarity between KBE and DT, where the latter serves as a support platform for KBE processes. It comes particularly from DT's ability to act as a recommendation system, storing and providing information that assists the engineer in defining functional requirements and conforming them to the project objectives.

The complementarity between KBE and DT has just recently started to be analysed in the literature, showing concepts of how KBE can be integrated with DT to benefit organisation operations.

According to Rebentisch et al. (2021), the DT adoption coupled with KBE could lead to partners and the market recognising organisations as leaders, increasing their reputation. Model-centric design, comprehensive PLM, rapid production of diverse design solutions, and a faster response through a faster knowledge flow were the required skills in this dynamic (Rebentisch et al. 2021). In addition, KBEs and DT approach also can help increase knowledge reuse during the engineering phase, which can positively impact the Transformer BU profit at Efacec (Azevedo, Tavares, and Soares 2020).

In addition, to achieve its strategic goals, DT and KBE must also be linked appropriately with

the organisation's high-level strategy. The organisation's strategic goals and objectives must be the beginning point for the DT implementation and definition.

2.5. Final considerations

DT is an emerging research and development topic, with most literature published after 2016. It is a relatively new topic compared with KBE systems that came into existence at the beginning of the 1980 decade and evolved through the following years.

However, the significant acceleration of technology in recent years activated the potential to transform the implementation of DT integrated with KBE methodologies from an idea to a possibility. It was feasible mainly due to the appearance of new applications, supported by the IoT, CPS, cloud computing, and the proliferation of sensors and advances in simulation and data analysis.

Although the advantages of a new technological context with the application of DT and KBE in the organisation have been pointed out, it is necessary to mention the challenges concerning implementation in the literature. The complexity of the technologies that DT accommodates and their advances to how an organisation operates necessitates addressing potential issues that may develop before, during, and after adoption.

Schleich et al. (2017) concentrated on data-related issues, like the difficulties of obtaining and handling massive data sets, formulating complicated system predictions, and synchronising the virtual and physical worlds (Schleich et al. 2017).

Grieves (2019) identified the key issues, citing security problems against intellectual property theft, an excess of non-useful data collected, and the lack of interoperability of information representations in multiple DT as critical issues that organisations should address (Grieves 2019)

Dohrmann, Gesing, and Ward (2019) pointed out the difficulty of change management at DHL, which is critical in preparing and educating employees, customers, and suppliers for a new way of working, and the unpredictability of the overall costs of deploying a DT (Dohrmann, Gesing, and Ward 2019).

For Rebentisch et al. (2021), many organisations implement DTs with a technology-centric focus, paying little regard to the organisation's ecosystem and business strategies. While most organisations recognise that changing work processes and organisational structures are critical to digital transformation, most fail to approach DT design from a holistic Socio-Technical systems perspective (Rebentisch et al. 2021).

Despite the challenges, the benefits of implementing DT and KBE alone or coupled are already known in the literature. Organisations benefit from optimising a product's lifecycle, increasing their competitiveness in the market. The benefit is also for workers who stop performing repetitive tasks and begin to dedicate themselves to developing more challenging and analytical tasks, adding more value to the organisation.

Based on the number of publications about both topics, it is expected that more academic works and industry studies concerning the use of DT and KBE will appear in the coming years, enriching the knowledge of both domains.

3. Methodological approach

Due to the characteristics of the research, the case study research method was employed to study the context of DT at Efacec. Yin (2008) defined case study research as an empirical inquiry that analyses contemporary phenomena in its real-life setting, when the boundaries between phenomenon and context are not readily visible, and when numerous data sources are utilised (Yin 2008).

Moreover, a case study is an appropriate research design when it is necessary to obtain holistic, concrete, contextual, and in-depth knowledge about specific real-world key characteristics, meanings, and implications of the subject. The method leads to an understanding of a particular phenomenon, but it is the case that should be paramount (Pickard 2017).

Case studies typically concentrate on qualitative data from primary sources such as interviews, observations, workshops, focus groups, and secondary data from the organisation's official records and documents. Nevertheless, they may also collect quantitative data at times.

3.1. Overall methodology structure

The following approach was employed in this dissertation, considering the nature and objectives of the research:

1. Develop a literature review focusing on KBE and DT domains;
2. Establish a research method based on the case study approach;
3. Collect and analyse existing documentation and partial results;
4. Collect data using focus groups and semi-structured interviews;
5. Analyse the results from the focus group, interviews, documentation and partial project results;
6. Develop improvement proposals for engineering processes and PT design.

The first two steps required a purely theoretical approach to the domains that fit the organisation's needs and the accomplishments of the dissertation objectives. Steps three and four focused on fieldworking at Efacec by collecting data interactively with employees and from the project development environment.

Finally, steps five and six referred to the analysis of the results and improvement proposals coupled with the specific objectives of the dissertation. Although it is an analytical phase after data collection, some interaction with Efacec was still required, albeit to a lesser extent, to clarify complementary issues.

3.2. Methods employed for data collection

The data collection process was divided into two steps. The first step was to collect the prior existing documentation concerning the PT design and engineering processes, explore the methods utilised for data collection, and analyse the partial results of the project.

The second step was dedicated to developing methods for data collection for the research focused on answering the research question. Further, the researcher also gathered new documents during the research, which were also considered for the data triangulation.

3.2.1. Collect and analysis of existing documentation and partial results

The TRF4.0 project aims to digitalise the entirety of the PT's lifecycle through its DT. The project intends to use innovative, emerging, Industry 4.0 technologies. The research group should execute diverse, interdependent tasks to reach the project objectives.

The following were the initial tasks of the TRF4.0 project to be carried out. The first one was dedicated to the project vision definition and was also the basis for the preliminary dissemination of the project. The second was related to the definition of high-level requirements.

For these two tasks, workshops and focus groups were held between the partners and other stakeholders, whose results converged in a vision statement that will guide the project. From Efacec, members of engineering, project management, and maintenance teams closely related to the PT ecosystem participated in the events.

The TRF4.0 research group performed these two tasks before this dissertation started. For a better understanding of the context of the starting point, fit and rationale of the research, it was opted to not only present the findings but also describe the whole process of data collection of the first two tasks, even though they have already occurred.

3.2.1.1. Vision definition

The first task of the deliverable intended to detail and refine the proposed and previously mentioned concepts involved in the paradigm change toward the DT and the definition of the project's vision. The latter was accomplished in a workshop where stakeholders provided a consistent and concrete foundation for TRF 4.0 and its scope.

3.2.1.1.1. First workshop briefing

A workshop is an interactive session where stakeholders work extensively on a problem or question. The method encourages participants to compare their constructs of reality through

debate, individual reading of personal experiences, and detailed case study reports. This process often brings together elements of qualitative research, brainstorming, and problem-solving, allowing participants to verify the integrity of their stories and investigate the researcher's interpretation of cross-case themes (Pickard 2017).

The first workshop was conducted via web conference on the 17th of November 2020 (annex 1). Its objective was to define the project's vision and strategic impact, the definition of the project goals and its expected impact on the Efacec organisation, considering a timeframe of 3 to 5 years.

Firstly, the introduction provided context for the workshop goals and objectives, the structure of the Efacec organisation and the project overview. Further, the four fundamental concepts of the project were discussed KBE, Lifecycle Management (LCM), Product-Service Systems (PSS), and AM. Afterwards, all project stakeholders were present and organised into four groups, corresponding with these pillar themes. The four concepts were discussed under three topics:

- What are the needs/challenges/opportunities and business/technological context?
- What are the benefits of TRF 4.0?
- What is the desired state we want to achieve (strategic impact)?

The dissertation focuses on KBE methods and LCM application over the DT. The results summaries will concentrate on those concepts only, despite the PSS and AM being discussed in the other two groups. The inputs from the PSS and AM were also analysed. However, it presents some overlapped statements and other statements that directly have very little to do with the objectives of the dissertation.

3.2.1.2. High-level requirements

The second task encompassed the first project activities and was dedicated to the project's high-level requirements. These affect the development of the DT as much as they will influence its supporting technologies.

A second workshop and a focus group session were organised to obtain responses supporting the formulation of the high-level requirements. The respective target audience, and in that order, was contacted and interviewed relative to the KBE, LCM, PSS and AM concepts to understand their struggles in detail and thereby refine and establish these high-level requirements.

3.2.1.2.1. Second workshop briefing

Like the first, the second workshop was conducted via web conference on the 10th of December 2020 (annex 2). The objectives of the sessions were to detail concepts approached during the first workshop and concept alignment between all the project consortium partners.

The opening provided context for the workshop goals and objectives, followed by an overview of the first workshop. Like the first workshop, the four fundamental concepts of the project were discussed, and all project stakeholders were present and organised into four groups, corresponding with these pillar themes. Three topics were presented to discuss the four concepts transversally:

- What are the features/requirements of a DT-based engineering/design of the PT?
- What are the expected impacts on the PT engineering/design processes?
- What are the needed competencies and infrastructures to implement a DT approach in the engineering/design of the PT?

3.2.1.2.2. Focus groups briefing

A focus group is a method in which a professional moderator leads a group interview with similar experiences, demographic features or both. Focus groups open lines of communication between individuals and count on the dynamic interaction between members to build data that would be unbearable to obtain using other methods, such as a one-on-one interview (Pickard 2017).

The purpose was to elicit high-level requirements for the DT platform in each phase of the PT lifecycle. The employed method juxtaposes current processes and tools with the DT capabilities envisioned in user stories (annex 3) and overall business goals to identify new capabilities and improve previously submitted ones. The stakeholders performed some tasks before the focus group started:

- Efacec led the preparation of a presentation which described current processes, including tasks, tools, and resulting information;
- INESC TEC led the preparation of a presentation which described the DT capabilities, DT-supported tasks, tools, and IM.

Efacec members attended the focus group related to their role in PT development. As a result, three focus groups were held in such a way:

Theme	Date	Target audience	Goal
Knowledge-Based Engineering	6th of May 2021	Engineering department	Elicit high-level requirements for the DT platform and services

Table 5 - Focus group schedule for KBE concept.

Theme	Date	Target audience	Goal
Lifecycle Management	9th of June 2021	Maintenance, Service, and Engineering departments	Elicit high-level requirements for the PT's Lifecycle Management services

Table 6 - Focus group schedule for LCM concept.

Theme	Date	Target audience	Goal
Innovation in Product-Service Systems	29th of July 2021	Service and Engineering departments	Elicit high-level requirements for the innovation in PSS services

Table 7 - Focus group schedule for PSS concept.

The events were conducted via web conference, and firstly, the introduction provided context for the focus groups goals and objectives (annexes 4, 5 and 6). After that, the participants were introduced, and the following discussion lines were proposed:

- Current processes and tools shall be discussed, focusing on their problems, shortcomings and needs, as well as areas more prone to be improved;
- Validate user stories according to feasibility, relevance, and utility.

Furthermore, for each proposed DT capability in the user stories, the following must be identified:

- Is it realistic/feasible?
- What design tasks does it involve?

- What aspects of design does it impact/improve?
- What problems are diminished/eliminated by it?
- What benefits shall arise from it?

The moderator introduced, moderated, and participated in the discussion. Afterwards, Efacec led the description of current projects, processes, and tools. Afterwards, INESC TEC led the presentation of user stories with DT-supported methods and tools.

Lastly, the members presented their points of view regarding current processes and tools, evaluated DT capabilities outlined in user stories, and proposed DT capabilities. The results summaries will concentrate on DT, KBE and LCM concepts despite the PSS being discussed in one of the focus groups.

3.2.2. Collect data using focus groups and semi-structured interviews

After analysing the data collection process and the related results obtained from the first two tasks, referring to vision definition and high-level requirements, the methods for data collection were defined.

At this stage, considerable concern was taken into developing the focus group and interviews. It was necessary to consider which participants had been present at the previous data collection, what questions they had been subjected to, and what type of answers had been given so that repeated or irrelevant questions were avoided, thus passing on a sense of continuity to the project.

3.2.2.1. Focus group

An online focus group (appendix 1) was scheduled and conducted on the 24th of January 2022. The objectives were:

- Macro exposition of the PT design process;
- Exposure from the macro point of view of some elements of the engineering team involved in the main stages of the project;
- Miscellaneous topics.

On the Efacec side, the participants were mainly from the Engineering and R&D departments and participants from other teams whose processes interact strongly with the engineering processes. The asked questions were around four major themes:

- KM;

- IM;
- Collaboration;
- Action Plans.

The researcher moderated the group discussion among the participants. As the information emerged, new relevant questions were asked so that a specific topic could be deepened interactively. The session lasted about an hour and a half and was recorded in video and audio formats for transcription. Also, written notes were taken to record participants' impressions and observations.

3.2.2.2. Interviews

Interviews are one-on-one, qualitative, in-depth conversations in which the researcher assumes the position of an investigator. This approach suggests that the researcher asks questions, manages the dynamics of the discussion, or converses with a single person at a time.

However, researchers play the facilitator or moderator in a focus group discussion. In this situation, the researcher moderates a group discussion between participants rather than between the researcher and the participants. In contrast to interviews, the researcher takes a supporting rather than leading role in a focus group discussion (Krueger and Casey 2000).

A questionnaire is a data collection technique used within various research methods, including the case study research method. It is at a minimal cost to reach a broad and geographically distributed group and collect data from a larger sample than any other method. Anonymity and secrecy are allowed, and data analysis can be planned before surveys are disseminated (Pickard 2017).

The use of questionnaires in research was premised on the idea that interviewees would be willing and able to provide honest responses. The pre-established questions may be self-administered, administered by mail, or asked by interviewers. When the questionnaire is administered by interview, it is often called an interview schedule (Burns 2000).

Questionnaire design is a time-consuming procedure that might imply the difference between a high response rate and comprehensive data or no data. The poor design would discourage participants from participating and increase measurement inaccuracy (Oppenheim 1992).

Research can use closed questions in questionnaires. There are three types of questions in this category: multiple-choice, dichotomous, and rank order. However, the dissertation will not use closed questions because the collection of very detailed information is the focus of the work. Moreover, respondents can provide answers they may not have considered, and those with no

opinions will also respond.

A questionnaire (appendix 2) with open-ended questions was developed to deepen and obtain more details about the product design and engineering processes through interviews.

The questionnaire started with a brief introduction for the participant, which explained the primary purpose of this interview: to understand and characterise the maturity level of KM in the engineering processes of the PT.

Regarding the questionnaire design, the first set of questions was related to subjects that were relatively simple to answer. Starting with questions such as how long the employee has been with the organisation and in what position. As the questionnaire progressed, more complex questions were asked after engaging the respondent (Pickard 2017).

Furthermore, funnelling techniques were applied, starting with broad questions and then progressively narrowing the scope of the questions until they came to specific topics (Oppenheim 1992). The questions were grouped into the following themes:

- KM processes, management and promotion of explicit, implicit and tacit knowledge and analytical culture;
- Technology issues at different levels, from IM to the use of IS;
- Processes and IM for the PT's lifecycle.

Before the disclosure, the questionnaire underwent several revisions, where the adequacy and formulation of the questions were discussed and reflected. It was also tested with people with research experience in the KM domain and an Efacec employee who contributed to adjusting the approach to the reality of the organisational culture. Following the development of the questionnaire, Efacec was contacted to identify the most suitable stakeholders to answer questions and schedule the interviews. The objective was to ensure that the questions were well understood by researchers specialising in the subject and Efacec employees.

Regarding the interviewees, the following criteria and people were chosen, totalling six interviews:

- Engineering department: three employees, including the leader of the area;
- Commercial department: one employee with a high position in the hierarchy and a broad view of the department;
- R&D department: one employee with intensive communication with the Engineering department;

- Project Management department: one employee with a high position and intensive communication with the Engineering department.

Interviews were conducted at Efacec in June of 2022 in a semi-structured manner. The data collection began as the questions were answered and through discussions with the stakeholders. Each interview lasted around an hour, and during data collection, an audio recorder was used so the information could be transcribed. Written notes were taken to record the impressions and comments from participants. It was explained to the interviewees that all collected data would be used solely and exclusively for academic purposes, with total anonymity and confidentiality of the information collected.

This semi-structured interview technique is more typical and follows a framework to manage essential themes rather than specific questions. At the same time, it permitted a certain degree of flexibility for the researcher to respond to the interviewee's answers and thus conceive the themes and topics as they emerge (MacDonald and Headlam 2015).

3.2.2.3. High-level engineering documents

The current high-level engineering process for the BOL stage of the PT was internally developed by Efacec. It starts with receiving the closed contract from the Commercial department and ends with the dossier containing the detailed instructions for designing and assembling the PT being sent to manufacturing. Although high-level, this process manages to detail the interaction of the engineering team with the other areas of the Transformer BU and the flow of information. The engineering processes shown are comprised of the BOL phase of the PTs.

The subsequent manufacturing, testing and customer delivery phases and detailing how Engineering and Project Management departments interact in this phase, although belonging to the BOL stage, are not specified. Similarly, the contractualisation process performed by the Commercial department is neither shown nor detailed in this flow. Although contracting is before PT's BOL, the process is still relevant, and when conducted with non-compliance, it impacts the whole supply chain.

The design also details the cyclic processes under the do-while loop and if-then statement logic that terminates only when the requirements are completely satisfied. Independently of this research, the design of this process goes through a constant process of evaluation and improvement. The customer is involved in all milestones to follow the project's progress and approve each step until the project is sent to manufacturing.

This complete process was shown to the participants right after the interview, and a debate

started. Participants from other areas that constantly interacted with the Engineering department during PT design were invited to point out critical bottlenecks and opportunities for process improvement. The suggestions, criticisms and debates were recorded, and the researcher took written notes to record the impressions and critical comments from participants.

The organisation also has conducted and shared a study for collaborative research purposes regarding the documentation collected for the requirements phase of the PT design process (annex 7) and a second study concerning employing simulation tools, which were also presented after the interview for discussion. Both studies analyse specific subprocesses of the high-level engineering process at BOL.

3.2.3. Data triangulation

Approaching the same problem from many perspectives will assist in constructing a comprehensive understanding of the phenomenon. Comparing various data sources, also known as data triangulation, has been proposed to improve the study's internal validity (Stake 1995). Miles and Huberman (1994) claimed that a fundamental premise is that data acquired in varying methods, apart from biases and contrasting strengths, should complement and lead to congruent conclusions (Miles and Huberman 1994). Yin (2008) also argued that triangulation gathers information from multiple sources but aims to corroborate the same facts or phenomena (Yin 2008).

The first step was to collect and analyse the existing documentation, the employed methodologies for data collection and partial results in the project development environment that was directly related to the objectives of the dissertation. Other documents were also collected, such as briefings, development and results of workshops and focus groups held before and during the research.

Furthermore, the transcriptions of the focus group and interviews were performed along with observation notes. Through the transcripts, the common themes of the research were identified, and annotations with relevant keywords, expressions, phrases, or section codes were made.

After analysing the transcription of the interviews, some additional questions were addressed via e-mail to the same respondents, aiming to clarify details or questions that remained open. The researcher incorporated the supplementary responses into the full transcription document.

Finally, the transcriptions were integrated with all the previously gathered documents to be catalogued, analysed, and organised into themes of interest for the research using the triangulation technique. It allowed specifying essential information types and patterns.

This strategy helped the development of the questions that were carried out in the focus group and interviews. In addition, the triangulation approach also helped compare the information from existing engineering processes against the information gathered from the focus group and interviews. This process needed to be rigorously and consistently conducted in formats that could be referenced and sorted to uncover research lines and convergent trends.

3.3 Result analysis and requirements development

The final task was to analyse the results obtained and develop requirements focused on the specific objectives of the dissertation, succinctly expressed as:

- Analysis of the existing product design and engineering processes;
- Characterisation, creation and dissemination of knowledge;
- Specification of the requirements for redesigned knowledge processes;
- Refining of DT data and IM model included in the DT digital platform;
- Development of a POC, including a knowledge lifecycle model;
- Assessing the impact on product design and engineering processes.

Different approaches were used to represent the recommendation proposals. The work employed flowcharts, conceptual schemes, and tables to organise the information and describe the dynamics of the model to be developed. Comparison with literature results was conducted to evaluate and validate the results obtained with the research.

In sum, it is expected that implementing the recommendations should impact the DT project positively, optimising the product's lifecycle and increasing the competitiveness of Efacec in a highly competitive market.

4. Case study description

4.1. The organisation description

Efacec Power Solutions is a Portuguese company operating in the energy, mobility, and engineering sectors in over 65 countries. The foundation took place in 1905, the year in which “A Moderna” Sociedade de Serração Mecânica (“The Modern” Mechanical Sawmill Society) was founded. Later, this organisation gave rise to Electro-Moderna, Lda. in 1921, initiating the production of generators, motors, transformers, and electrical accessories.

The brand Efacec arose in 1962, and since then, the organisation has grown steadily, forming a group of companies known as Efacec Power Solutions. The conglomerate encompasses all modes of production, technologies, and technical and human skills in energy, engineering, environment, transportation, and electric mobility. At the end of the 1960s, Efacec became one of the first Portuguese companies listed on the Lisbon Stock Exchange.

Presently, Efacec is an organisation that operates in the global market and whose strategy of growth in the international market has been based on the presentation of innovative and quality products. Its constant adaptation to keep its status as a large industrial organisation at the national and international class is reflected in its mission:

“We create value with Energy, Environmental and Transportation solutions that improve everyone’s day-to-day lives by bringing together different skills and innovative technologies. We develop people in an organisation of learning and continuous improvement.”

Also, its vision states:

“Anticipating solutions for a sustainable world in the new energy Era.”

Efacec operates in three industrial centres in Portugal, the Polo da Maia, Lagoas Parque, and Parque da Arroteia, totalling 2.400 employees.

4.2. The Transformer Business Unit

4.2.1. Business Unit organisation

Unlike a more traditional hierarchy, relationships between BU departments are configured as a grid in a matrix structure. It is a sort of organisational administration in which individuals with equivalent skills are pooled for work duties, resulting in more than one manager. For instance, all engineers may be in the Engineering department and report to an engineering manager. However, these same engineers may be assigned to different projects and report to

project managers. Therefore, some engineers might have to work with multiple managers in their job roles.

There are eight departments, three of which act as support areas for the entire BU:

- **Administrative Support:** Is responsible for optimising the administrative management and ensures travel logistics, hotels, vehicles rent, visas, service cell phones and fuel cards;
- **Operational Control:** Is responsible for reporting project results and analysing business concerning operational and technical indicators. Also, it supports budget and performance control elaboration;
- **Lean:** Is responsible for improving the efficiency of operations within transformers and Servicing BUs. Further, it is in charge of reducing the lead time from the reception of the order until the delivery of product/service and improving the on-time delivery and quality.

The other five core departments are:

- **Commercial:** Is responsible for the strategy of the organisation's commercial vision and guarantees alignment with the global strategy through the implementation of sales processes and the competitiveness of the offers;
- **Technology:** Is responsible for the vision and strategy of the organisation's technological evolution, ensuring the alignment of the technology roadmap with the organisation's global strategy through implementing processes related to R&D, Engineering, Product Management and Certifications;
- **Operations department:** Oversees the organisation's vision and integrated strategy concerning production activities and developing turnkey projects. It also ensures the dynamics between business support areas, corporate departments, and other transversal ones;
- **Project Management:** Is responsible for implementing processes which assure the most significant autonomy and commitment to the customer: satisfaction, on-time delivery, and non-quality costs. Also, it guarantees the focus on the critical path and value chain of projects;
- **Quality:** It promises customer satisfaction with segregation and quality reinforcement. Further, it reinforces the internal systems and guarantees the execution of proceedings, tool usage and control of quality cycles.

The Engineering department is part of the Technology department and was the focal point of interaction with the organisation. Its primary focus is promoting continuous improvement of engineering output and its competitiveness and control of non-quality costs. Further, implementing an innovative, competitive, and robust design for all products ensures a governance model, strategy, and synergies common to all engineering teams.

4.2.2. Transformers projects development dynamics

The development of PT projects at Efacec involves iterative procedures requiring exchange and collaboration between product development team members, the departments linked to the different phases of the PT's lifecycle, and the customer. As a result, the design activities of transformers are transversal to the organisation, involving the Commercial, Project Management, Product Development, R&D, and Production departments.

The Commercial department is primarily responsible for the initial communication with the customer, carrying out a primary survey of requirements and technical specifications. The Project Management department works with the Product Development department to create and potentially complement the project requirements, contacting the customer after each work milestone to inform him of the project's status and collect his feedback.

The Product Development department performs all engineering studies and calculations that contribute to the design of the PT and then transmits all the necessary specifications to the production team. The team comprises a leading engineer, senior consultants, and a set of engineering cells composed of one team coordinator and various engineers.

4.3. Products & services portfolio

Efacec is one of the world leaders in the design and manufacturing of PT and offers a portfolio of three products: Power Transformers, Mobile Substations, and Distribution Transformers. In addition, the organisation provides services for repairs and maintenance dedicated to single-phase and three-phase oil-filled PTs, Autotransformers, Shunt Reactors, and Mobile Substations (on-site services) up to 745kV.

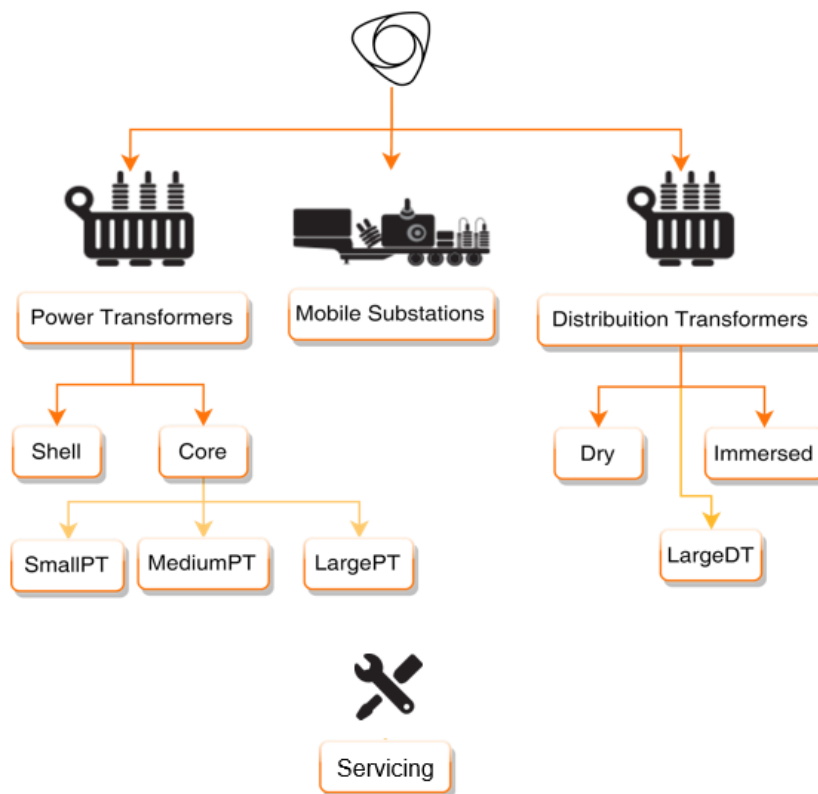


Figure 17 - Full products & service portfolio.

4.4. The Power Transformer

A PT is the product object of study. It is a device that transmits electrical current from one voltage level to another without changing the circuit's power. The principle governing the operation of the machine is not the movement of its components, since they are static, but the electromagnetic induction between the primary coil and one or more secondary coils wrapped in a ferromagnetic core.

This process results in the reception of alternating current electrical energy by the primary coil, which converts it into magnetic energy, followed by the secondary coil's conversion of this energy into electrical current. The voltage conversion can be from the lowest to the highest, or vice versa, with the PT responsible for this conversion being called step-up or step-down transformers, respectively.

The most frequent locations where step-up transformers are installed are electrical substations that efficiently transmit energy over long distances. In contrast, step-down transformers are often used in factories, shopping malls and homes to reduce voltage to the level of operation of

appliances and other equipment.



Figure 18 - The Power Transformer.

4.5. The Transformer 4.0 project

Industrial organisations are under pressure to increase critical knowledge from data analysis insights that lead to innovative product design and integrated services regarding engineering and maintenance processes. Existing PT development processes are traditional, depending on document-based information exchange and a set of PLM and simulation instruments that are not interconnected. This scenario makes it difficult for the PT business to evolve toward data-driven LCM.

The DT concept and associated Industry 4.0 technologies offer an opportunity for the organisation to accelerate the digital transformation process of the PT business and promote the integration of information and data originating from diverse sources, offering services that facilitate the development of the PT and add value to the device, beyond its operation and maintenance.

The enabling technologies include approaches and techniques such as KBE, Model-Based Systems Engineering (MBSE), IoT, Big Data Analytics and AM (3D printing). These technologies are expected to place the DT as the virtual counterpart of the physical product, improving product design, manufacturability, performance, longevity and safety throughout its lifecycle.

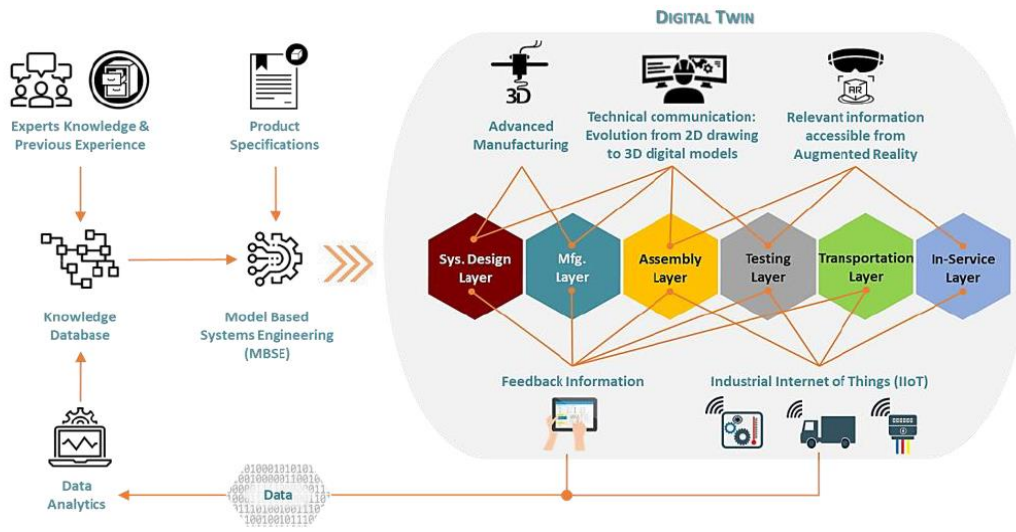


Figure 19 - TRF4.0 project overview. TRF4.0 consortium, internal document.

The TRF4.0 project seeks to develop digital transformation in the PTs. The platform will board a set of decision support tools in the form of services expected to develop the current PT design processes towards a KBE paradigm. It enhances and promotes the multi-stakeholder management of the PT's lifecycle and supports business and engineering decision-makers in developing new product-services-based business models.

5. Results

The presentation of the results was divided into two parts. The first part presents results from the initial two tasks of the project held before the dissertation. It starts with the findings from the vision definition obtained through workshops and follows with the findings related to the description of high-level requirements obtained through workshops and focus groups. The findings collected from these previous phases helped tailor the subsequent data collection processes.

The second part presents the research findings concerning engineering processes and lifecycle based on data collected from the focus group, interviews, and new documents collected during the research. Some questions proposed for the focus groups and interviews in this phase were similar to those in previous phases. This fact is not necessarily a limitation and was done purposely to deepen the answers and give the participants a sense of continuity to the project. Further, a result summary is shown at the end of the chapter.

5.1. Research results from previous project tasks

This section describes the results obtained from the TRF4.0 research group before the dissertation started.

5.1.1. Vision definition

From the workshops, annex 8 summarises the participants' input on the KBE concept, and annex 9 contains a summary of the participants' input on the LCM concept.

For the KBE concept, the findings were:

- The technological context compels for advancements in data analysis, knowledge capture, storage and dissemination, new ways to interact with the product, and new knowledge tools;
- The market context beckons for a modular, more standardised product which stands out with added value and includes the involvement of the customer throughout design and manufacture, all of this through the DT;
- Some opportunities to explore are the servitisation, already demanded by many customers, capture, storage, and management of all types of knowledge within an organisation through appropriate tools to do so, promotion of knowledge sharing habits and an actively engaged knowledge community implementation of system engineering practices.

In the same way, for the LCM concept, the findings were:

- There is a need to have dynamic exploration of the DT, process optimisation and even maintenance improvement;
- The benefits of the project would be to optimise the lifespan of the product, promotion of interoperability of the different and heterogeneous sources and the possibility of network management through the PT;
- As for the strategic impact, the project would open the door for developing new data-centric services and healthier, longer-lasting PTs.

5.1.2. High-level requirements

Annex 10 summarises the participants' information on the KBE concept, and annex 11 contains a summary of the participants' input on the LCM concept. Also, the outlines aggregate together the results of the workshop and the focus groups.

For the KBE concept, the findings were:

- The high-level technological requirements reinforce the necessity of a robust analytics ecosystem, including interoperability and more agility in data and information processing and AI for optimisation opportunities;
- Implementing a structured KM aims to retrieve historical information quickly and easily, focusing on tacit and implicit knowledge. Stimulation for knowledge sharing and strong communication efficiency among the team members and between the organisation and customers;
- The information is dispersed and not categorised. It is not easily recoverable, and it is necessary to go through all the designs to get results relevant to current projects, e. g., tests and other types of data that need to be manually recovered from PDF files.

Also, regarding the LCM concept, the findings were:

- Evolution from descriptive analysis to cognitive analysis for forecasting and improvement, e.g., lifespan boost, acoustic emissions, reduction of unplanned maintenance operations due to equipment outages;
- Enrichment and broad distribution of generated data through comprehensive, cutting-edge technology, e.g., fibre technology. Online monitoring of the DT from all stakeholders for a more efficient decision-making process;
- An improved product design and more flexibility to meet customer requirements and

change the product even in later stages of the lifecycle. Identification of design restrictions under manufacture and legislation contexts;

- The organisation must establish strong communication with customers and suppliers during the lifecycle. In addition, aggregation and organisation of the collected information are needed from these interactions.

5.2. Research results for engineering processes and lifecycle

This section describes the results obtained directly from the research and was divided according to the method used. First, the findings obtained from the focus group will be shown and then the findings from the interviews. Finally, the results from supporting documents with proposals for improvements in the high-level engineering processes will be described.

5.2.1. Focus group

The focus group results were divided into five sections: KM, IM, Collaboration, Action Plans and Engineering Processes. The discussion of the first four themes was already foreseen since the event's conception. The last one concerning Engineering Processes emerged naturally during the conduction of the event and was stimulated because although it was not the central theme for this event, it is one of the central themes of the dissertation. The relevant extracts were transcribed in the following sections with the respective analysis.

5.2.1.1. Knowledge Management

The current processes still do not allow information to be distributed widely and evenly among all team members due to the lack of a robust methodology that ensures access to all, including new team members, as stated by participant 1: *“we try to pass on this knowledge in the most efficient way so that it does not get lost in that moment that is easier, normally sending an e-mail saying [...] I solved it this way, and you send it to the team [...] lessons learned: we do not do it because we have many projects, which were not even very viable.”* Moreover, participant 1 continued: *“there are the people who were not part of the team at that moment not receiving an e-mail, then they do not even have access to the information.”*

Participant 4 contributed to the same subject by reporting the lack of a unified database for data retrieving: *“these internal discussions are often particularised between the various teams [...] if we have new colleagues involved in projects [...] it is a difficulty we have because we do not have a database with this information that can be consulted across the board by people.”*

Regarding the tools and possible integrations, initiatives were reported using automation tools

for knowledge storage. However, the current scenario still treats information in several applications not connected among themselves. Participant 4 stated: *“in theory, we have, and we have been trying to work on some automatic tools, and these tools are a base where we deposit the knowledge, and they are the ones who then treat it [...] we still do not have automation and many times what we do not have is an easy way to register and pass this information.”* Furthermore, participant 1 reported, *“[...] we have several tools that help us execute tasks of the engineering process.”*

The organisation’s ongoing move towards digital transformation is also an additional barrier as processes have changed, impacting the documentation process. As participant 3 said: *“the process is quite different from what it was two or three years ago, and we cannot document everything simultaneously as the process evolves. I think that is a serious difficulty.”*

PLM management is still under development. For now, Product Data Management (PDM) methodologies are still applied. As participant 1 reported, *“We do not have it yet. We are working on it [...] the commercial tool we thought of and are using is turning out to be a PDM, not PLM.”*

5.2.1.2. Information Management

Participant 1 stated that the participation of the engineering team should happen at the beginning of the project to better define the offer and align expectations between what is sold by the organisation and what the customer expects to receive. It is suggested that this process could qualify the data received by engineering and contribute to a better definition of the offer for the customer: *“no, we do not have all the data whenever we need it. That is, if we were involved at the beginning of an engineering project, born as an order from a customer [...], it would be perfectly defined what was sold [...] and what the customer bought.”*

Furthermore, participant 1 added, *“we have some situations in which when we are working and refining the product requirements, with additional data, we realize that the product specified by the client is different from what the customer thinks he bought.”*

Participant 2 stated that part of the responsibility for poor quality specifications lies with the customer: *“the customer himself is also not sure how to specify more correctly the product he wants.”* Moreover, participant 3 affirmed, *“[...] that makes communication in our engineering phase more complex with constant involvement to clear doubts, questions.”*

Participant 4 reported that there could be better integration and use of good practices between the Engineering department and Tendering, which is a specific area of the Commercial department: *“one of the things that can also be claimed at the moment is that tendering lacks*

data to be able to also do the work more in line with the latest engineering practices.”

Moreover, participant 1 added, *“the package of information that reaches us is confusing. It brings contradictory information, i.e., many documents reach us, some with no relevance to engineering [...].”*

5.2.1.3. Collaboration

There was unanimity in the group that collaboration is essential for higher quality in the final delivery to the customer and needs improvement. At the current moment, collaboration occurs more intensely in project meetings, as reported by participant 4: *“Internally in engineering, we end up having this by collaboration with the meetings [...] then we have other steps that happen in all projects that can allow collaboration between engineering and production as well, for example [...].”*

Furthermore, participant 4 continued: *“in the end, it is a moment that can be used and that we want to be used to exchange knowledge [...] we have this perception that collaboration is essential to achieve a product that is increasingly suitable and of better quality.”*

5.2.1.4. Action Plans

The responses provided by the participants show that the PTs' occurrence monitoring system is relatively mature, that action plans emerge, and that decision-making occurs when necessary. In the corporate and departmental context, the development of action plans for engineering process improvement does not occur, as participant 1 affirmed: *“we have occurrence management. In other words, when a defect is detected, a severe one, or one that is detected with many recurrences, an analysis is done, and an action plan emerges.”* Moreover, participant 1 related, *“We have a system of occurrences, where non-conformities are registered [...] this incident management platform also allows recording opportunities for improvement, and they always arrive for engineering to analyse.”*

The nature of the action plan applied in the PTs can be of the preventive or corrective type. Participant 1 reported: *“there are corrective actions and preventive actions. That is, the corrective action to correct that defect and the preventive action to change whatever needs to be changed [...].”*

Additionally, a dashboard with indicators displays the state of occurrences and the stakeholders to whom the event is attributed. In the words of participant 1: *“we have a dashboard that tells us how many occurrences are open, how many of those were originated in co-responsibility for engineering, how many originated with responsibility for suppliers,*

with responsibility for logistics, with responsibility for operations, with the various departments [...] there are various indicators.”

5.2.1.5. Engineering Processes

There is a clear perception that engineering processes need to be optimised, especially for PT projects that are outside usual standards, such as highly customised projects with high complexity, as stated by participant 1: *“we know that we have to modify some designs because we will not have the conditions to manufacture that design for having some dimensions and some superior masses according to the normal process that we have.”* Moreover, participant 1 related that *“what we have not been able to do is for those more complex designs, and when we do the engineering design, we already detect that it will be even more challenging to manufacture.”*

Regarding design for manufacture, the issues related to circularity, i.e., design for disassembly, analysis of materials, and identification of materials that can be used, are still an aspect that needs to be developed. As reported by respondent 4, *“I think there is still a way to go regarding the recycling part of it, but as we are in the introduction phase of the structure, and we are focusing more on the technical part and creating the technical basis of our tool, I think it will be something to review afterwards.”*

It is understood that the role of the DT will be to correct, organise and store the data generated by the PT during its lifecycle. The engineering team understands that this data draw essential knowledge for the design of the PT from its life in terms of operation, as confirmed the respondent 1: *“manufactured machines with the same considerations for different customers will have different maintenance schemes [...] there is one that has problems in a particular aspect than the other, and that may have to do with the maintenance plan, one being better than the other, this would also allow us not only to recommend the maintenance to our customers, having more data to make a better recommendation [...].”*

5.2.2. Interviews

The results of the interviews were divided into the themes on which the questionnaire was based: KM processes, management and promotion of explicit, implicit, and tacit knowledge and analytical culture; technology issues at different levels, from IM to IS; processes in the PT's lifecycle context.

5.2.2.1. Position in the organisation

The respondents were from the Engineering, Commercial, Project Management and R&D

departments and had between 5 and 15 years of work at Efacec. Some respondents have passed through other areas within the corporation, and others have been in the same department since they started working at the organisation, moving up through the hierarchy. Regarding seniority, the respondents were in leadership positions in their departments, and among these, one was in an executive position.

5.2.2.2. Knowledge Management Processes

Some respondents did not perceive that the organisation has established a strategy or a structured institutional discourse about the importance of KM to increase the organisation's competitiveness. On the other hand, some perceived an organisation movement in search of implementing a KM strategy.

It was unanimously reported that the processes of storing and recovering data, information and documents are carried out in different applications, which inevitably implies the loss of time in each phase and the mandatory insertion of duplicate data. These applications have unique rules for registering these elements; generally, they are not connected. The rules for storing, updating, and recovering are not described, depending on the worker to remember the necessary steps needed to be performed in the applications. There is concern concerning data reliability because of intensive manual intervention.

All departments reuse data, documents and knowledge acquired in previous projects, but in different scopes, frequencies, and needs. In the same way that elements are stored and recovered, the reuse process is hindered due to element dispersion across applications and the lack of knowledge recording. In addition to being decentralised, it does not have the same search criteria between diverse project parameters. A possible exception was reported by the respondent from the Commercial department, who stated that the Tendering area could quickly and easily recover information from past projects to reuse.

Another difficulty reported by the Project Management and Engineering departments is the lack of project document versioning management. It is impossible to know if the document in a particular folder is the most recent one. There are also no previous versions of the same document, so the history of modifications and comments added over time cannot be analysed.

Electronic sharing of documents was not considered a barrier. Respondents pointed out that the current corporate tools, Microsoft Teams and SharePoint, meet this need and other cited resources such as e-mail. On the other hand, the respondent from the Project Management department affirmed that there is no ingrained culture of actively sharing information with colleagues. On the other hand, respondents pointed out that colleagues, when consulted,

readily collaborated by providing the necessary information.

Among the necessary and currently non-existent instruments for promoting and managing tacit knowledge, the respondents unanimously pointed out: Mentoring programs encourage senior workers to train juniors through classes, lectures, and hands-on activities.

The respondent from the Commercial department reported that there is no mentoring but that there are training and annual recycling projects in Tendering. In short, there is no recurrent individualised follow-up after these training events.

The R&D respondent indicated that in the past, there was organised mentoring with knowledge transfer, known as training. The respondent is unaware that this process will continue and recognises that a resumption would be positive, especially for integrating new employees.

Another instrument also mentioned as desirable is Question and Answer (Q&A) tools, for workers to post questions that their subject matter experts can answer. There, workers could search and get answers and best practices. The Project Management respondent considered Q&A a helpful tool as time is wasted with repeated questions.

These instruments already exist, but improvements could be implemented:

- Face-to-face or online meetings to discuss projects and inform workers concerning the characteristics, objectives and expected results, among other topics;
- Face-to-face or online meetings for case studies to share success stories, failures, and lessons learned with customers (debriefing);
- Tutorials, in text format with videos and audios, so that workers can replicate more complex techniques and actions and up-to-date content.

Regarding the meetings, the respondents pointed out weaknesses in the lack of organisation of the event. The absence, many times, of a work agenda and well-defined objectives was reported. There is also a lack of good management of the meeting agenda, the definition of the following steps, the results to be achieved, and finally, the meeting minutes creation and sharing. Another issue reported by respondents was the need for meetings with an expanded and transversal scope between departments to exchange information due to gaps and weaknesses in the handover processes. The respondent from the Commercial department stated that there are weekly internal meetings with three well-defined themes: commercial, tendering and management.

For the tutorials, the suggestion to update some outdated information was reported. The respondent from the Project Management department also claimed that Efacec uses a third-

party platform with generic training content not specific to the organisation.

For the instrument:

- Collaboration in the workplace, using collaborative suites like Trello, Basecamp and Teamwork.com for process tracking;

Although not directly cited in the sentence above, respondents cited Microsoft Teams for messaging, collaboration, and information sharing.

One of the respondents from the Engineering department brought up a reflection on the search for knowledge of previous projects. It was reported that when it is known that a particular person participated in a project, that person will be consulted either because he has a memory or because he knows where he kept the documents, and not because the knowledge is stored or recoverable in the systems.

Knowledge is not shared evenly among all teams, especially with new members. When someone new comes in, or someone is not very familiar with it, and there is no conversation, in these cases, the progress of the project gets hampered.

The respondents unanimously never experienced or witnessed the loss of critical project data due to internal failure, industrial espionage, or cyberattack.

5.2.2.3. KM from the perspective of processes and analytical culture

Regarding culture and analytical processes, the respondents see that there is room for the organisation to improve its analytical culture, which now presents different degrees of development between the Transformer BU departments.

The Commercial and Project Management departments present culture and well-structured analytical processes, with periodic meetings, for constant evaluation of KPIs and development of action plans with the assignment of deadlines and responsibilities. It was also reported that dashboards are updated as often as necessary.

On the other hand, respondents from the Engineering and R&D departments do not have this culture established. According to the report of the respondents from the Engineering department, action plans are generated as needed, and managing the achievement of KPI results is not a routine. One respondent from the Engineering department affirmed that result analysis is mandatory to understand if the processes are running as presupposed and to observe performance indices to evaluate the employee results.

None of the departments uses any statistical method of trend analysis or recommendation systems supported by AI that could suggest an optimised arrangement of product offerings and

associated services, projection of results, or even improvement of the PT design. The respondent from the Commercial department related the purchasing of external reports and research to prepare their internal analyses of the market trends.

The respondent from the Commercial department affirmed that the organisation uses the Balanced Scorecard (BSC) since the respondent mentioned the measurement of financial results and customer satisfaction, including metrics of internal business process and learning and growth. The respondent stated that the organisation does some BSC exercises in Transformer BU.

The BSC retains financial metrics as the outcome measures for organisation success but supplements these with metrics from three additional perspectives – customer, internal process, and learning and growth – proposed as the drivers for creating long-term shareholder value (Kaplan 2009).

5.2.2.4. Technology-focused on Information Management

Data quality was below what was expected by the respondents, who pointed out negative biases to varying degrees in all criteria: Availability, Precision, Relevance, Consistency and Completeness.

In general, all data needed to execute the tasks is either unavailable or takes time to arrive. The respondent from the R&D department reported that it was necessary to interact actively with other departments to get the data. Some data are trapped in the IS database, others on the engineering side and not on any platform. The respondent from the Commercial department presented a moderately different response, who reported that the department has all the data required for decision-making and that the considered criteria have satisfactory positive biases. On the other hand, it is still necessary to work manually with the data a little more on the Tendering side.

In general, much time is wasted separating relevant data from irrelevant data. One of the respondents reported the finding of irrelevant data because no application or report goes straight into the searched data.

Respondents pointed out that inaccuracies and missing data, depending on the situation, also appear occasionally and cause them to spend time searching for the most accurate or missing information.

Inconsistency occurs between different data sources. One respondent reported that data consistency depends on context: data acquired at the level of technical definitions are consistent. On the other hand, the data acquired at the team planning and time management

level is hardly consistent. There were situations where the same data, information and documents were present in two or more sources, but because of different update timings, they appeared differently.

Regarding the manual and automated processes for data consolidation and the time spent on these processes, there is no total consolidation of these data in one place. The workers must use two or more IS to retrieve the data.

Respondents from the Engineering department reported that 50% to 60% of weekly working hours are generally spent consolidating data in a repetitive and low-value-added process until they transform data into valuable information. The respondent from the Project Management department stated that about a third of the time is spent on data consolidation.

The respondent from the R&D department reported that the time spent depends on the project. One respondent reported spending from half to a whole working day on the consolidation, representing 10% to 20% of weekly working hours. The Commercial department respondent claimed that the time spent on manual processes is minimal, about 5% of the weekly working hours and that much of the information is already consolidated in automated dashboards.

The respondents agreed that this effect occurs not only because of data but also because information and documents of the projects are being spread among the various IS and folders without any connection or reference between them, making it impossible to query and retrieve the information in a unified interface.

One Engineering department respondent claimed that the organisation already has some automatic tools. The most time-consuming process always starts by reading the specifications and extracting and loading the data. Then some manual calculations are made using spreadsheets. Another part is already automatic, i.e., the data is introduced, and the platforms generate the solution.

Data and information from customers and suppliers needed for project management are not available for immediate consultation, requiring the request to be made through telephone or e-mail. The respondent from the R&D department reported that it is common for data and information to be updated on the supplier side and not shared with Efacec. Consequently, the organisation is not aware of this update, and a new request for the update of the documents is necessary. The respondents unanimously reported that improving this process would optimise project development.

At the same time, respondents from the Commercial and Project Management departments considered that maintaining telephone and face-to-face contact is a helpful way to strengthen

ties with partners industry with conservative players in an ultra-competitive market scenario.

5.2.2.5. Technology-focused on applications, software and IT management

For contextualising, applications and software refer to corporate IS such as ERP, CRM and Office Suites, and engineering legacy applications. Respondents pointed out that management is agile in acquiring and updating the organisation's IT infrastructure. Some respondents pointed out that although the required technological tools are implemented, sometimes training or training updates do not coincide, making adopting the tools more painful. One respondent detailed that there were tools introduced impulsively, and there was no time to mature the product definition in the application. There was no more dedicated and focused training on what was performed.

Unanimously, the respondents declared that all the necessary applications are available without missing any that prevent or hinder their professional performance. A specific exception was pointed out by two respondents regarding the need for software for resource planning for a given project, to implement, for example, the allocation of hours of a worker in each project and the fulfilment of tasks.

Regarding the criteria considered in the software qualification: Speed, Flexibility, Reliability, Correctness and Updating. Overall, more positive than negative biases were reported across all criteria to varying degrees. One respondent related particular and isolated cases of crashing and freezing of application processing were reported, and when they happened, it caused the worker to lose several working days. Occasionally, respondents pointed out less flexible tools for adapting to the personal working methods, such as the ERP and some software with previous versions concerning the last release. Finally, for one of the respondents, the speed of the internal network was considered a weak point in the IT infrastructure, as it makes it difficult to share and stores documents in the correct repository.

Regarding the integration between tools, the respondents pointed out that the integration is between weak and moderate and that it is a process in development. There is a platform that will do the full integration, and during that process, there are concerns regarding information consistency between the various applications to be integrated.

The consumption and manipulation of data from cell phone data or other small-screen portable devices seem more valuable and relevant for the Project Management and Commercial departments. For the Engineering and R&D areas, this feature did not seem suitable or desirable.

5.2.2.6. Engineering processes focused on the PT's lifecycle

5.2.2.6.1. Beginning-Of-Life stage

Regarding how collaboration between departments can help to optimise the PTs design, it was suggested by the respondent from the Project Management department that for projects with a higher level of complexity and a personalised work model, there should be closer integration between four entities: Tendering (Commercial sub-department), and those responsible for the project from the Commercial, Engineering and Project Management departments. This integration should occur from the closed contract milestone until the engineering handover.

It was also argued that in this work model, the exchange of information between all the parties involved could be carried out more fluidly and assertively, where everyone would be aware of the same information at the same time, instead of the serial work model, where the tasks, once completed, are handed over to the next player.

The respondent from the Commercial department reported the existence of a working model involving several areas for cases of complex projects. He also added that for these complex projects, the tendering team works closely with the technology and engineering teams and that a risk exercise is elaborated, in which the different areas are invited to comment. When a project is won, there are handover moments and kickoff meetings for more complex projects.

5.2.2.6.2. Middle-Of-Life stage

Data from the PT currently in operation are not yet extracted and analysed to improve product design and create new services.

The respondent from the Commercial department recognised the importance of obtaining data from the PT to expand the service offer. However, it reported a severe barrier to obtaining data from customers' PT.

Most of the customers who were consulted refused to share the data because they considered it sensitive, reserved, and confidential. For the customers willing to give up the data, it would be necessary to establish a data disclosure agreement, security requirements and very restrictive DM. The respondent also reported that the organisation must discuss this barrier internally with higher levels.

The areas unanimously considered essential to obtain this data. Specifically, the respondents from the Engineering department reported the importance of understanding the operating characteristics of the PT for the design improvement.

The respondent from the Commercial department claimed not receiving customers' demand

for new services. From the customer's perspective, for now, Efacec does not present an apparent deficit in offering new services.

Regarding the intelligence in the operation of the PT, it was reported by the respondent from the Engineering department that the current management logic of the PT operation is based on a type of manually programmed decision tree that promotes optimised operation for specific conditions and that also avoids the product to operate in hazardous envelopes that could reduce life expectancy. It has been reported that PTs can currently suggest maintenance earlier than usual and forced ventilation depending on the PT load, which is still a way for the PT to work more efficiently.

5.2.2.6.3. End-Of-Life stage

The respondent from the Commercial department reported that the business still does not have much weight in the EOL stage. Some request information comes to Efacec from customers regarding what materials can be recyclable and what to do with them. The respondent also stated that the organisation would be required to address relevant issues such as sustainability in the future.

5.2.3. High-level engineering processes analysis procedures

In the following two subsections, two improvement proposals already developed in the TRF4.0 project that could contribute to optimising the engineering processes will be presented. The first one is about KM processes facing project complexity and the level of commitment from the customer concerning the delivery of the requirements. The second proposal implements simulation tools that give life to the PT's DT and contribute to the agility of the project design. Both improvements came from internal documents of the project, and discussions were held after the interviews.

5.2.3.1. Project requirement analysis

Three transformer projects were used as models, each with differing degrees of agility at getting the entire list of requirements needed for the start of the transformer design conceptual design:

- PT 001: It is considered the “*good*” model in which Efacec elicited the transformers' requirements quickly;
- PT 002 and PT 003 are considered “*bad*” models in which Efacec did not obtain the complete list of transformers' requirements quickly and efficiently.

Firstly, the consumer submits its requirements in a document prepared by the customer or an

intermediary agent, generally a consulting firm. This documentation is then internally analysed and translated into a more structured and consistent internal document. The customer documentation can be extensive, necessitating more discussion to be successfully translated into specifications.

The project manager handed over the project to the Engineering department. At this point, the contract between Efacec and the customer is closed. Nevertheless, that does not mean that the requirements are fully translated into specifications and that there is space for discussion to establish the final documentation.

The organisation fully developed the improvement suggestions, and the researcher, during one of the fieldworking at Efacec, requested some clarifications from the engineering team to understand the recommendations and subsequent integration with the complete improvement proposal.

It was possible to reach the following findings from the analysis of this process applied in three models:

- The greater the volume of documentation that must be stored, the more challenging this step in the design process is, and the more critical it is to maintain track of information;
- The most important it is to retain a record of all stakeholder interactions and correspondence;
- The two projects with the most challenging requirements to translate, PT 002 and PT 003, have the most customer documentation and, as a result, a more significant number of rules, standards, and legislation to follow;
- The small number of examples makes it impossible to conclude potential language barriers.

It is necessary to mention that the customer of PT 001, who is Portuguese, reached Efacec directly. On the other hand, customers of PT 002 and PT 003 contacted the Efacec delegation in the local country, which helped to overcome language obstacles and ensured a deeper relationship with the customer.

5.2.3.2. Simulation integration framework

This section presents and describes the design and simulation tools currently applied in the development of the Core-type Transformer, mapped in the business development of the PT. Planning for implementing these simulation tools is already one of the TRF4.0 project tasks.

It will be used and coupled with the other ideas put forth in this work as another element that will help optimise the engineering processes in the BOL phase of the PT.

The opportunity to increase productivity lies in the phase right after the project is presented to the specialist team of the Engineering department. During one of the fieldworking sessions at Efacec, the engineering team also addressed the specifics of the implementation. As it is a theme with exhaustive technical detailing and is critical for the organisation's strategy, the researcher decided to adopt a more broad and abstract approach.

In terms of findings, it is possible to deduce that correctly implementing these simulation tools could improve efficiency in the engineering process and give the first breath of life to the virtual part of PT, also known as DT. Several physical, real-world characteristics will be simulated by different models, such as finite element models for electromagnetic, fluid, and mechanical design.

To support integration, the models must establish semantic interoperability to guarantee that a construct in one model has the same semantics as a corresponding construct in another. Additionally, communication between modelling tools must include this information.

5.3. Results Summary

The first section will summarise the results obtained before the beginning of this research by the TRF4.0 research group. The second part will summarise the research results concerning engineering processes and lifecycle based on data collected from the focus group, interviews, and new documents collected during the research.

5.3.1. Vision definition and high-level requirements

The results presented by the workshop and focus groups showed that the organisation understands the challenges of the paradigm shift. The vision incorporated, among other factors, Industry 4.0 technology enablers for exploiting PT servitisation through analytical strategy, methods, and tools.

Another essential point that the vision definition provided was the understanding that the KBE processes are strategic for the organisation to manage and leverage the knowledge generated to benefit an efficient LCM for the PT.

Discussions of the needed high-level requirements for the project pointed out bottlenecks and elucidated some challenges the organisation needs to overcome to optimise its engineering and lifecycle processes, such as the need for more flexible product design. The details raised at this stage exposed, also the need for better communication processes with customers and suppliers.

The discussions also reinforced and detailed the need for better management of the currently dispersed and hard-to-recover information and pointed out the need to manage the implicit and tacit knowledge that today is not being used efficiently.

5.3.2. Engineering processes and lifecycle

The results summary of the research were grouped in the following themes:

Knowledge Management Processes
Strategy • The perception that the organisation has established a strategy or a structured institutional discourse about the importance of KM was mixed. Explicit knowledge • The processes of storing and recovering data, information and documents are carried out in different applications, which inevitably implies the loss of time in each phase; • In the same way that elements are stored and recovered, the reuse process is hindered due to element dispersion across applications and the lack of knowledge recording; • There is a lack of project document versioning management. It is challenging to know if the document in a particular folder is the most recent one; • Electronic sharing of multimedia was not considered by the organisation a barrier. Tacit and implicit knowledge • For the promotion and management of tacit knowledge, the following instruments were considered the most important: Mentoring programs to encourage senior workers to train juniors through classes, lectures, and hands-on activities, followed by Q&A tools;

- For tutorials, the suggestion was to aggregate videos and audio to the text so that workers could replicate more complex techniques and actions. Up-to-date content was also required;
- Regarding the meetings, it was pointed out weaknesses in the lack of organisation of the event. Many times, a work plan and well-defined objectives and agenda are missing;
- Regarding collaboration tools in the workplace was cited Microsoft Teams for messaging, collaboration, and data sharing;
- There is no ingrained culture of actively sharing information with colleagues. Knowledge is not shared evenly among all teams, especially with new members.

Table 8 - KM processes summary.

KM from the perspective of processes and analytical culture

Strategy

- There was a perception that there is an opportunity for the organisation to improve its analytical culture, which presents different degrees of development between the Transformer BU departments.

Operations

- The Commercial and Project Management departments were the areas that presented some culture and well-structured analytical processes. On the other hand, respondents from the Engineering and R&D departments do not have this culture well established;
- None of the departments uses any statistical method of trend analysis or recommendation systems supported by AI that could suggest improvements.

Table 9 - KM from the perspective of processes and analytical culture summary.

Technology-focused on Information Management

- Data quality was below what was expected. The organisation pointed out negative biases to varying degrees in all criteria: Availability, Precision, Relevance, Consistency and Completeness;
- Two criteria proved more critical than others: data Availability and Consistency across databases and application data;
- In Engineering and Project Management departments, time is spent on manual processes for data consolidation, which in some cases can take up to half of the weekly working time until transform data into valuable information;
- The available data and information from customers and suppliers are not the most up-to-date, requiring updating the request. The data and information are also not directly available to everyone in the organisation;
- It was never experienced or witnessed the loss of critical project data due to internal failure, industrial espionage, or cyberattack.

Table 10 - Technology-focused on IM summary.

Technology-focused on applications, software and IT management
Strategy • The organisation's management is considered agile in acquiring and updating its IT. On the other hand, training or training updates do not coincide, making adopting the tools more painful. Operations • With few exceptions, all the necessary applications are available without missing any that prevent or hinder their professional performance; • Regarding the criteria considered in the software qualification: Speed, Flexibility, Reliability, Correctness and Updating. Overall, more positive than negative biases were reported by the organisation across all criteria to varying degrees;

- Two criteria proved more critical than others: Reliability and Flexibility. The speed of the internal network was considered by the organisation a weak point in the IT infrastructure;
- The integration between tools is considered weak to moderate and a process in development. The lack of integration forces consultation on the same project in different applications;
- The consumption and manipulation of data from cell phone data or other small-screen portable devices seem more valuable and relevant for the Project Management and Commercial departments.

Table 11 - Technology-focused on applications, software, and IT management summary.

Engineering processes focused on the PT lifecycle
BOL • An identified necessity to integrate the teams more closely in projects with a higher level of complexity with the use of a personalised working model between the four entities: Tendering, Commercial, Engineering and Project Management departments; • An identified necessity to optimise the engineering process by implementing integrated IS where data could be retrieved, updated and inserted at specific flow points and milestones to speed up the completion and validation of the requirements, among other documents; • The greater the volume of documentation that must be stored, the more challenging this step in the design process is, and the more critical it is to maintain track of information; • Implementing simulation tools could not only improves efficiency in the engineering process but also gives the first breath of life to the virtual part of PT, also known as DT. MOL • Data from the PT currently in operation are not yet extracted and analysed to improve product design and create new services;

- A severe barrier to obtaining data from customers' PT was identified. Most of the customers whom the organisation consulted refuse to share the data because they considered it sensitive, reserved and confidential;
- The current management logic of the PT operation is based on a manually programmed decision tree.

EOL

- The requested information comes to Efacec from customers regarding what materials can be recyclable and what to do with them;
- It is believed that more will be required from the organisation in the future to address relevant issues such as sustainability;
- There is little business interest or strategy intelligence regarding the processes of collecting, remanufacturing, disassembly, recycling, reuse or disposal.

Table 12 - Engineering processes focused on the PT lifecycle summary.

There are considerations regarding the bias of the responses obtained in the focus group and interviews. Specifically, the researcher detected contradictory perceptions and reports concerning the effectiveness of the meetings between departments to discuss projects.

This effect probably happened due to the different views and positions of the respondent in the hierarchy. Also, in specific topics, respondents with higher hierarchical positions were perceived to have a more political and reserved discourse when reporting some sensible internal problems of the organisation, possibly to preserve the organisation's image, not wishing to expose the weak points in a pronounced way.

These results are related to achieving the specific objective of the dissertation, Obj3.1: Analyse the existing product design and engineering processes.

6. Implementing the Digital Twin concept

Implementing the DT concept to PT development involved identifying key features and capabilities of this emerging technology, followed by analysing current Efacec processes. The organisation can establish PT development processes employing knowledge by coupling the identified DT capabilities with Efacec KBE bottlenecks. With the optimisation, it is expected that the organisation could offer the market a more competitive and aggregated value product.

6.1. The Power Transformer virtual modelling

To model a physical product reliably and precisely, the DT must be able to replicate all its properties. In the case of the PT, this involves modelling the machine's geometric, mechanical, and electromagnetic characteristics. Therefore, the DT is required to include virtual modelling functionality.

Geometric modelling refers to the components' appearance, dimension, and position. The mechanical properties include the component's movements and the type and mass of the material used in the composition. Finally, the electromagnetic properties of the PT should also be replicated by the DT, which involves modelling the behaviour of the electric circuit and magnetic forces that the machine handles while in operation.

Furthermore, a crucial part of implementing the DT is establishing a bidirectional data transmission channel between the virtual and the physical PT, enabling the DT to receive sensor data from the physical PT and send real-time commands.

On the other hand, it risks information security, as this data is strategic and valuable and can be the subject of industrial espionage. Consequently, organisations should ensure encrypted communication between the DT and the PT.

The final aspect regarding DT modelling is the digital infrastructure from which this application can be visualised and utilised, as the contexts in which the DT will be accessed require that it be able to be visualised through multiple devices.

Considering the definitions attributed to the DT concept by the most recent literature, as by Qi and Tao (2018), it is possible to assert that this technology comprises three main components:

- The physical PT;
- A digital model accurately representing it;
- A bidirectional data transmission channel to connect both.

The model for collecting and processing this data depends on the stage of the PT. The BOL

stage depends on the organisation's current process and the ability to integrate all information and IS into a unified vision for the same project.

In the MOL stage, the data collection is performed by the PT sensing. This data is sent to an IoT network and stored in a repository. In the EOL stage, the information relates to the fate of the PT as a whole and its components. The collected data informs about why, how, and when partners gather, disassemble, remanufacture, recycle, reuse, or discard.

Considering the heterogeneity shown in each stage, developing a robust and economically feasible framework is necessary. Data integration also requires the integration of the organisation's IS. External information to the organisational context will also be considered, such as customers, suppliers, and the industry environment.

The following sections will describe and detail the proposed model, methods and processes implementations that will contribute to optimising product design and engineering processes.

6.2. Defining a query mechanism for Digital Twin information

As established, the DT will function as a knowledge base that engineers can access to support their design tasks. As a result, it is essential to implement a query mechanism that permits the fast and effective retrieval of the information stored in the platform. This process involves describing, classifying, and organising all captured and generated artefacts and attributing metadata to them.

Traditionally, the retrieval of digital document-based information is executed through term-based querying, a technique that involves the return of a set of documents based on user search terms. Although this can be an effective way of retrieving information if engineers are familiarised with the terminology and contents of the document corpus, the complexity and longevity of PT engineering information make the use of the query search terms technique practically inefficient, as the documents contain information related to multiple engineering branches and tasks.

Furthermore, this is aggravated by the absence of context offered by term-based querying, which generally relies on the user's understanding and interpretation of their informational need to successfully retrieve a target document (Giess, Wild, and McMahon 2007).

This issue can be surpassed by implementing a search mechanism that provides a predetermined structure in which documents are organised. It enables the user to comprehend each concept and context in the documents, allowing for more practical information retrieval.

Two query mechanisms permit information retrieval through a predetermined structure: the

enumerative and faceted classification schemes.

An enumerative scheme partitions concepts into a hierarchical arrangement until each describes a specific topic. A problem with this type of scheme is the difficulty in selecting the top and lower-level concepts, and the criteria governing these choices profoundly impact information retrieval, as it can steer a scheme towards users from a particular branch of engineering compared to others.

Conversely, a faceted classification scheme involves the development of facets that describe a concept, and these facets can be combined to describe all the concepts that a specific document has concerning the information. As a result, no viewpoint is prioritised by the query structure. A faceted classification scheme is a type of query mechanism that permits information retrieval through a predetermined structure and involves the development of facets that describe a concept.

The development of a faceted classification involves determining critical concepts within a document that can be combined to describe the complete information and then develop facets based on those concepts (Miguel Azevedo 2020). For this reason, a faceted classification approach was employed to describe DT information.

6.2.1. Describing information for Digital Twin

The provision of relevant information is a considerable challenge in engineering design, where for engineers to carry out their tasks, they must be able to access and incorporate various information resources. The information is generated by different teams in various documentary representations and stored in different IS.

An engineer may search for information for which the title, description or location is unknown and where the specific terminology may not be fully understood. Moreover, a significant proportion of engineering documentation is informal, communicative documentation such as e-mail, meeting minutes and working documentation such as analysis files.

Such files are essential to documenting engineering activity, as they support the more formal documentation. These are not written as a formal record but as a means of communication in carrying out work (Giess, Wild, and McMahon 2008).

In the case of PT's DT information, faceted classifications were developed by first describing the information contained in each type of engineering document, followed by developing facets and subfacets that accurately describe the documents.

These tasks accounted for the primary goal of providing an easily understandable and efficient

method for information retrieval by PT development stakeholders, regardless of the field of expertise or role in the organisation.

6.2.2. Defining facets

During the research, each type of documentation regarding the concepts it contains, how it is organised, what format it is in, what task or process created it, and what purpose it serves to describe the information from the DT was envisioned. This process resulted in the identification of various types of documents.

The overall goal of this task was to create a robust classification scheme that could accurately describe any DT document, allowing for information retrieval through various query strategies not only for the use of the engineering team but also from the other teams of the Transformer BU.

The proposed faceted classification, in appendix 3, shows the structure relating to the facets, subfacets, and descriptions for engineering processes. The facets describe the information relating to the PT characterisation and operation. Further supporting faceted classifications describe other pertinent information to Transformer BU, allowing the DT to deliver the required knowledge.

The following shows the purpose of the facets regarding the PT characterisation and operation:

- Design Rule: Describes documents that contain restrictive information regarding PT design;
- Design Model: Describes models created during engineering design, and the models accurately represent the mechanical, electric circuit, and magnetic circuit properties of the PT;
- Instructional Documentation: Employed to classify documents that contain information that helps engineers determine what, how or when to do a specific task during design processes;
- Administrative Documentation: Describes documents that support the PT development process;
- Component: Details the PT component that a given document has information about;
- Clamping Element: Refers to the devices or processes that support, divide, or connect PT;
- Parameter: Describes documents that detail the properties of PT components;

- Service Information: Describes information that originates from tasks executed on the PT during its operation or is created by the PT operation itself;
- Lifecycle Phase: Relates to the stage of PT's lifecycle in which the document or data was produced or captured;

Next, the purpose of the facets regarding other pertinent information to Transformer BU:

- Customers: Describes documents that contain information from customers related to engineering activities;
- Suppliers: Describes documents that detail information from suppliers related to engineering activities;
- Competition: Describes documents detailing competitors' information of interest to engineering and other areas related to the development of the PT;
- External macro factors: Describes documents containing information of interest to engineering relating to factors impacting the entire transformer industry;
- Insight: Describe documents that contain information that may improve or otherwise modify PT design;
- Date: Describes various date formats required to establish a temporal reference to data, information, or documents;
- Format: Describes the format in which the document or data is presented. Some values considered are CSV, TXT, PDF, XLXS, PPT and Custom formats.

All the facets are related to each other, which is mandatory since data, information and documents will be necessarily related and integrated into the repository. This way, it will be possible to run queries that go through all facets, considering an appropriate information retrieval context.

For instance, to illustrate an inappropriate information retrieval context, a query tries to return an operation result from a specific PT while still in the design phase. In another situation, obtaining the design data will not be possible because the contract has not even been closed.

Faceted classification allows users to find items based on more than one dimension. For example, one user may be interested in retrieving the Electric Circuit Model and Calculus Manual documents concerning the projects from one specific customer between 2019 and 2021 in PDF format. Besides searching for information, other types of queries can be executed, such as updating, adding, or even deleting data, information, and documents.

It is evident that faceted classification in some form or another now plays an integral part in most methods of information retrieval. It is well established as a construction method in classification schemes and thesauri and has affected the development of even the most conservative systems in traditional document description and organisation (Broughton 2006).

These results are related to achieving the specific objective of the dissertation, Obj2.2: Refine the DT data and IM model included in the DT digital platform to meet the requirements of the knowledge-based processes.

6.3. Creation and dissemination of knowledge from AI services

An integrated model was developed to characterise the creation and dissemination of knowledge obtained from AI services that explore the data from the DT. The faceted classifications made it possible to propose an integrated model that considers other critical data sources and technical artefacts contributing to requirement meetings.

The proposed model shown in figure 20 is dedicated to creating and disseminating DT knowledge from the AI. The data flow between almost all components involved is bidirectional, meaning the system is data-driven. The exception is ingested data from industry environment data, which is unidirectional.

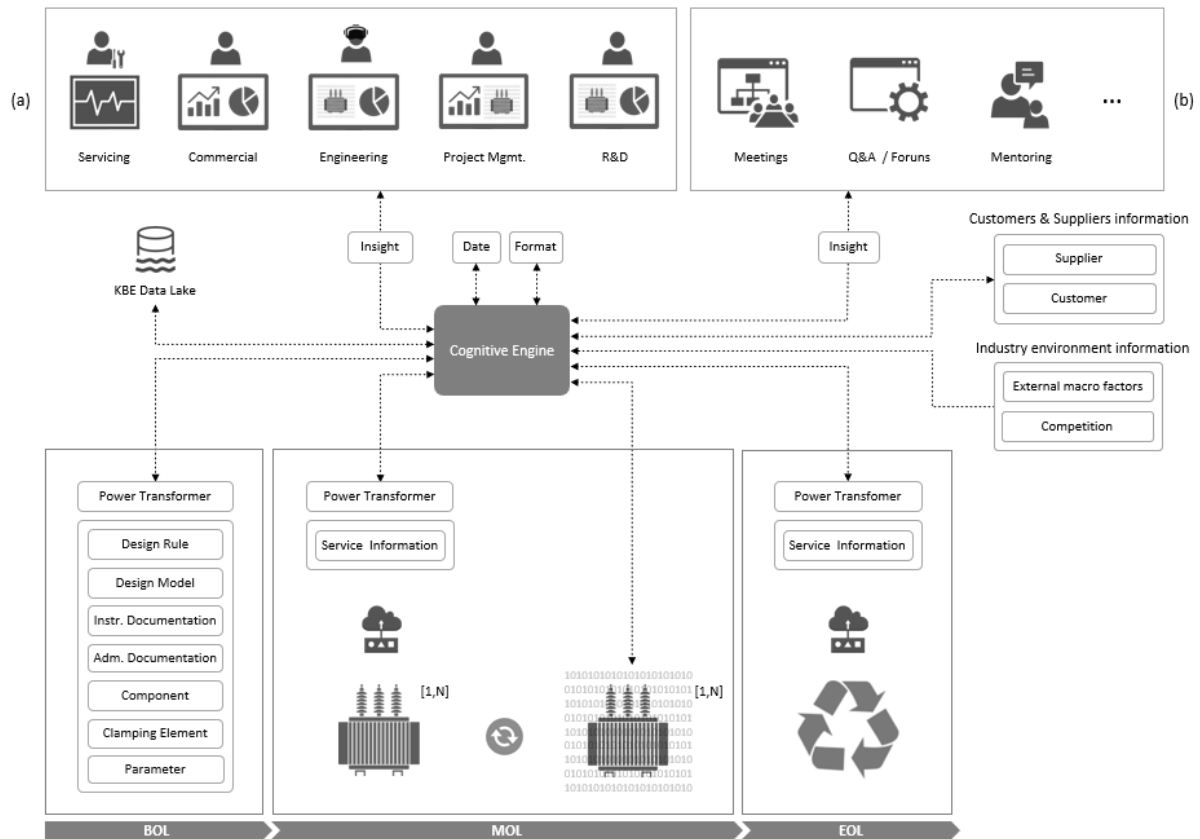


Figure 20 - An integrated model for knowledge creation and dissemination. (a) Knowledge consumption, composition, and dissemination from and for the teams; (b) Tacit and implicit Knowledge consumption, co-creation and dissemination.

Data Lake (DL) is an approach enabled by robust, low-cost technologies that use data repositories to enhance the assemblage, refinement, archiving and exploration of data within the organisation. It is typically built to handle large and quickly arriving volumes of structured, semistructured, and unstructured data from which further insights are derived. The lake starts with raw data and matures as more data flows in while users and machines build up metadata and user adoption broadens (Stein and Morrison 2014).

The DL often contains a semantic database, a conceptual model that leverages the same standards and technologies used to create Internet hyperlinks and adds a layer of context over the data that defines the meaning of the data and its interrelationships with other data. The DL strategies can combine SQL and NoSQL database approaches Online Analytical Processing (OLAP) and Online Transaction Processing (OLTP) capabilities. In contrast to a hierarchical Data Warehouse with files or folders, the DL uses a flat architecture, where each data element has a unique identifier and a set of extended metadata tags. This associated technology enables DT to run different types of analytics, from dashboards and visualisations to Big Data processing, real-time analytics, and ML to guide better decisions (“What Is a Data Lake? Store All Your Data in One Centralized Repository at Any Scale” 2018).

If required, the DL can be divided into three tiers: one for raw data, a second for augmented daily datasets and another for third-party information. Among the possible types of items that DL can ingest are logs and sensor data, social media, document collections, geo-location trails, images, video and audio and other helpful information for integrated analysis (Miloslavskaya and Tolstoy 2016).

The complete data, information and documents are concentrated in the KBE DL, ensuring a single, integrated view of any project or customer. The information comes from the PT's lifecycle and external contexts, such as customers, suppliers, and the industry environment. Furthermore, the faceted classifications offer the query mechanism for data, information, and document management.

The information from the BOL stage typically comes from corporate IS such as ERP, CRM and Office Suites, and engineering legacy applications, while the MOL stage data comes from the operation of one or more PTs. In the EOL stage, information can come from PT or components still in activity and information concerning how they were collected, disassembled, remanufactured, recycled, reused, or discarded. This architecture involving IM in all three

lifecycle phases is supported by the literature and addressed in the studies by Zheng, Lu, and Kiritsis (2021) concerning CDT and in the studies by Barricelli, Casiraghi, and Fogli (2019) and Riedelsheimer, Dorfhuber, and Stark (2020) for other industries.

In terms of the industry environment, the data, information, documents, and reports from the external macro factors that impact the whole industry of transformers and from the competition are ingested. All the documentation gathered from the transformer industry should be of interest to the engineering and development teams who can improve or otherwise modify the PT design. For instance, supposing that it is relevant to know what features are most common in PTs sold in certain countries, what direction the energy matrix of that countries will take in the coming years to anticipate the needs and, together with the other areas, develop an intelligent offer.

The information from the suppliers includes ready-to-query data, up-to-date product and service catalogue documents, contact information, and the record of interactions, among others. From customers, in addition to business information for establishing communication, the record of interactions and up-to-date business information could offer opportunities for upselling and cross-selling services and products.

The information concerning the date and format is of general use. It can be applied and integrated into all queries executed in the model to give temporal context to the information and format context to decide what file formats to use for collection, processing, archiving, and long-term preservation of the information.

The Cognitive Engine (CE) is a knowledge-base, reasoning engine, and learning engine to drive software modifications (Clancy et al. 2007). The collection of Machine Learning (ML) and AI algorithms of the CE is the driving force of the entire system, coupling all the data and information that flow from and for the model's components.

CE interacts directly with the KBE DL through the faceted data structure to obtain the stored information from the PT's lifecycle, customers, suppliers, and industry environment. This information is processed, and the insights are delivered to the teams in (a) and to the Knowledge-based systems and events in (b) to support the meetings, mentoring, Q&A, forum systems, and co-creation events with helpful information. The reverse information flow is also proper; the CE obtains new inputs from (a) and (b); evaluates and stores them into the KBE DL.

This CE is a core capacity not only to answer complex business questions asked by the senior management and technical team but also because the PTs are expected to be able to perform tasks autonomously. The PT is expected to incorporate features to execute, for instance, self-

diagnosis for loss of life detection and degradation assessment; dynamic exploitation for self-healing and adaptive control; intelligent sensing for self-adaptive data stream; safety for critical factors measurement in real-time and adaptive management.

From the physical PT perspective, the collected data from the sensors of one or more physical counterparts go through the IoT network and come to the CE to be processed and finally stored in the KBE DL.

Knowledge and information from DT are then delivered to (a) and (b) to support decision-making. Workers may also interact with the DT to navigate data pages or even intervene in a controlled manner in the operation of the PT.

From the perspective of the participants of each team in (a), they could receive pre-configured and configurable insights and analysis on a specific project or set of tasks. Workers can also actively interact with the system by submitting relevant business questions that will support the execution of their tasks.

As expected, the DT must aggregate real-time and historical data and information regarding the product, the physical product's digital counterpart. The virtual peer supports the physical counterpart's simulation, decision-making, failure prediction, and control, as Weyer et al. (2016) suggested.

Furthermore, there is an interactive optimisation between the PT and its DT and from them with the rest of the model components. This interactive model is supported by the literature, as Fei Tao and Zhang (2017) proposed a data-driven model with interaction between all model components.

The proposed development is consonant with the definitions that authors such as Ammar-Khodja, Perry, and Bernard (2008) and Rocca (2012) have given to KBE as an approach applied during product design. Even if this data refers to a post-design context, the insights developed from data of later stages will necessarily support the optimisation of the design stage. For instance, the operation characteristics of the PT, the competitor's movements, the development of new components and the upgrades from suppliers could be incorporated into the design to deliver a more optimised PT.

Moreover, even if the KBE DL refers to an artefact for the use of the Engineering department, the other departments from the Transformer BU could benefit from the resources offered to improve their processes and decisions supporting, even for PT post-design stages.

These results are related to achieving the specific objective of the dissertation, Obj3.2: Characterise the creation and dissemination of knowledge obtained from using AI tools that

explore the data from the DT.

6.3.1. Use cases for Cognitive Engine

Developing use cases is necessary to describe some applications of how users will perform tasks and how the system will behave. Business questions formulated by the workers can involve any subject concerning the PT's lifecycle stage and a wide range of subjects concerning customer, supplier, and industry environment perspectives. The CE is the instrument designed to answer these questions.

The CE receives the business questions from the workers or even automatically from other IS. The CE queries the KBE DL through the faceted data structure and processes the retrieved data, information, and documents, as illustrated in figure 21.

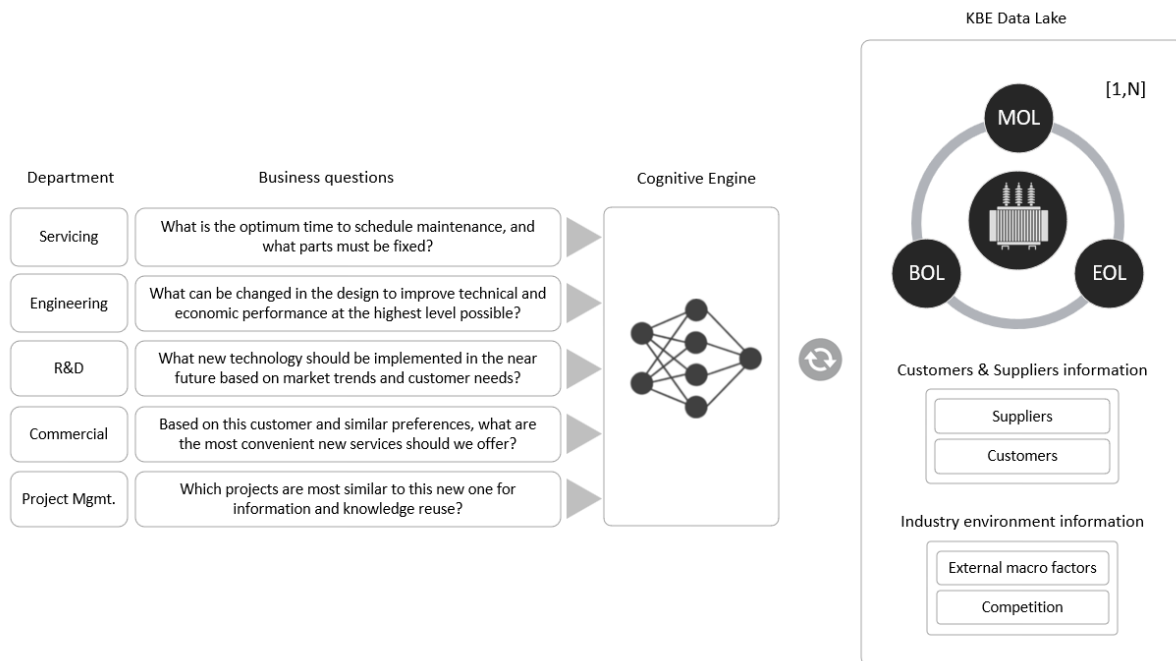


Figure 21 - Typical business questions performed to the CE by workers.

The business question formulated by the R&D department, “*What new technology should be implemented in the near future based on market trends and customer needs?*” demonstrates the importance of adding the industry environment data to the model for aggregating information, public or purchased, beyond those technological evolutions and innovations brought by suppliers. External information from factors such as technology and competition could enrich the internal information obtained from customer technology-oriented surveys. The identified new features of the components could be compared with the current PT design to evaluate the compatibility for a possible near future upgrade.

The Commercial department also could benefit from external data sources to answer the business question, “Based on this customer and similar preferences, what are the most convenient new services should we offer?”. It could be considered the information source from the actual customers and aggregate external information from economic factors regarding strategic countries to understand their current and future energy matrix, anticipate necessities and develop a more intelligent offering.

In figure 22, the CE replies with an answer depending on the context. The solution could be more restricted to a single subject or aggregated, covering a wide range of topics. The workers could eventually receive non-required insights from the system with relevant issues that will support the execution of the tasks.

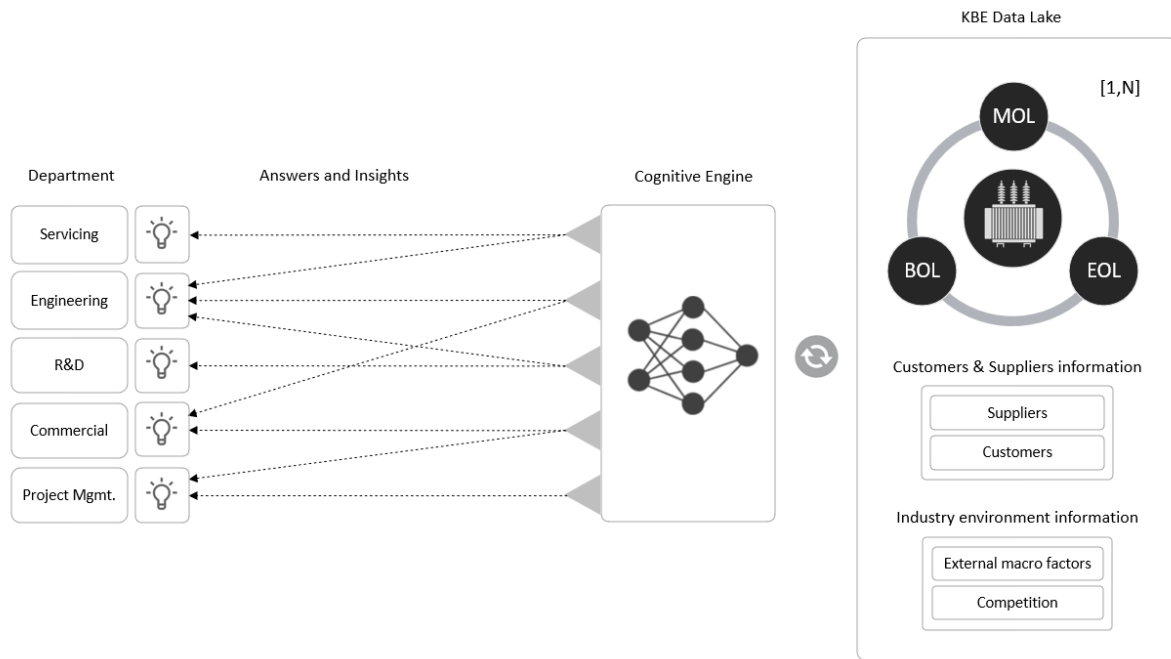


Figure 22 - The delivered answers and insights to the workers.

The planned DT-based Digital Platform Architecture for Efacec is more detailed than the one shown in the model in figure 20. The proposed architecture includes components such as the Data Orchestration Tool (DOT), a data layer responsible for data persistence and structuring that integrates traditional storage forms and the semantic infrastructure. It is crucial for integrating the data recovered from the multiple instances of DTs and fully realising the interoperability between different twin systems.

The second key component is the Business Orchestration Engine (BOE), a tool layer consisting of a modular set of tools. Leveraging the data and information from the data layer delivers the platform’s core functionalities. Finally, the Digital Twin Orchestrator Engine (DTOE), placed

at the core of the architecture, extends past the data layer to the tools layer.

The objective of the model proposed by the dissertation is to bring a more comprehensive view by introducing the concepts of CE and KBE DL, which include other business issues of the organisation beyond the data generated by the PT alone and workers. The model does not contradict or conflict with the planned DT-based Digital Platform Architecture proposed for Efacec. Instead, the models combine, seeking to optimise engineering and lifecycle processes.

It was expected to describe the ideas for services and suggested features, such as the general design and specific features, and how to achieve them utilising a POC. However, it was not possible to deepen the research and obtain enough information during the fieldworking at Efacec to develop a POC. At least it was possible to develop a use case that suggests some applications.

These results were supposed to achieve the specific objective of the dissertation, Obj1: Develop a POC for a part of a process, including a knowledge lifecycle model, from data to knowledge, methods for collaboration fostering knowledge sharing, and new information/knowledge practices.

6.4. The requirements for redesigned knowledge processes

The proposed specification of the requirements for redesigned knowledge processes leveraged in new data and information structures centred in the DT will encompass the entire organisation's data portfolio and the main areas of the Transformer BU.

Two sets of requirements were proposed, one focusing on KM in a general way that will affect the engineering processes and the whole organisation. The second set of requirements focuses on the PT's lifecycle and the aspects that will directly impact the engineering processes and the interfaces of this area with the other departments to create synergy in the process of PT optimisation.

Each requirement (appendices 4 and 5) has an identifier, the theme and subtheme, the requirement description, and the impact it provides. Regarding the themes, each requirement is organised into distinct topics, from addressing technical aspects of DT, such as data integration and analytics and lifecycle stage, to issues linked to changing the organisation's culture.

These results are related to achieving the specific objective of the dissertation, Obj2.1: Specify the requirements for redesigned knowledge processes leveraged in new data and information structures centred in the DT.

6.4.1. Knowledge Management requirements

Some considerations regarding the organisation of these requirements are necessary. The faster adoption of KM practices depends on implementing data quality practices (Kaufmann 2001) and software engineering best practices (Chang 2001). Due to this strong relationship, the IM and software and IT requirements will be integrated under the KM requirements umbrella. Also, although it is not a central theme of the dissertation, the approach to organisational culture will be listed and considered in what concerns better management of the KM. The KM requirements are shown in appendix 4.

6.4.2. Lifecycle requirements

The requirements will cover the three stages of the lifecycle: BOL, MOL and EOL. They are organised according to the nature of this requirement, which can be an aspect related to IM, engineering processes, or analytical methods for optimising the DT operation.

Some considerations regarding the organisation of these requirements are needed. Although it is referenced, for instance, that the DT should store information and provide query mechanisms, among other operations, what is behind the DT are IS, the CE and the KBL DL that work coupled to provide these functionalities to the DT. The lifecycle requirements are shown in appendix 5.

6.5. Digital Twin data and Information Management model

The current engineering processes are not supported by an integrated IS powered by ML algorithms, which maintains the operation inefficient. The organisation should integrate a CE-powered IS into certain phases of the high-level engineering processes so that improvements can become a reality.

In practice, the CE-powered IS will allow all the teams to consult information from similar past projects or to complete the specification document faster and be able to consult and include essential details in handover meetings.

Use cases were proposed, presenting how the workers perform tasks and how the sharing and collaboration occur, enabling knowledge-based processes. Furthermore, it will be possible to demonstrate that these processes will meet the KM and lifecycle requirements specified in the previous section.

6.5.1. Use cases for Knowledge-Based Engineering processes

These use cases will represent part of a process, exemplifying collaboration methods fostering

knowledge sharing and features of the knowledge lifecycle.

A worker should search for information concerning one or more stages of the lifecycle of one or more PTs of a particular customer. The worker performs one specific query in the IS employing the faceted classifications. The request arrives at the CE that queries the KBE DL, as illustrated in figure 23.

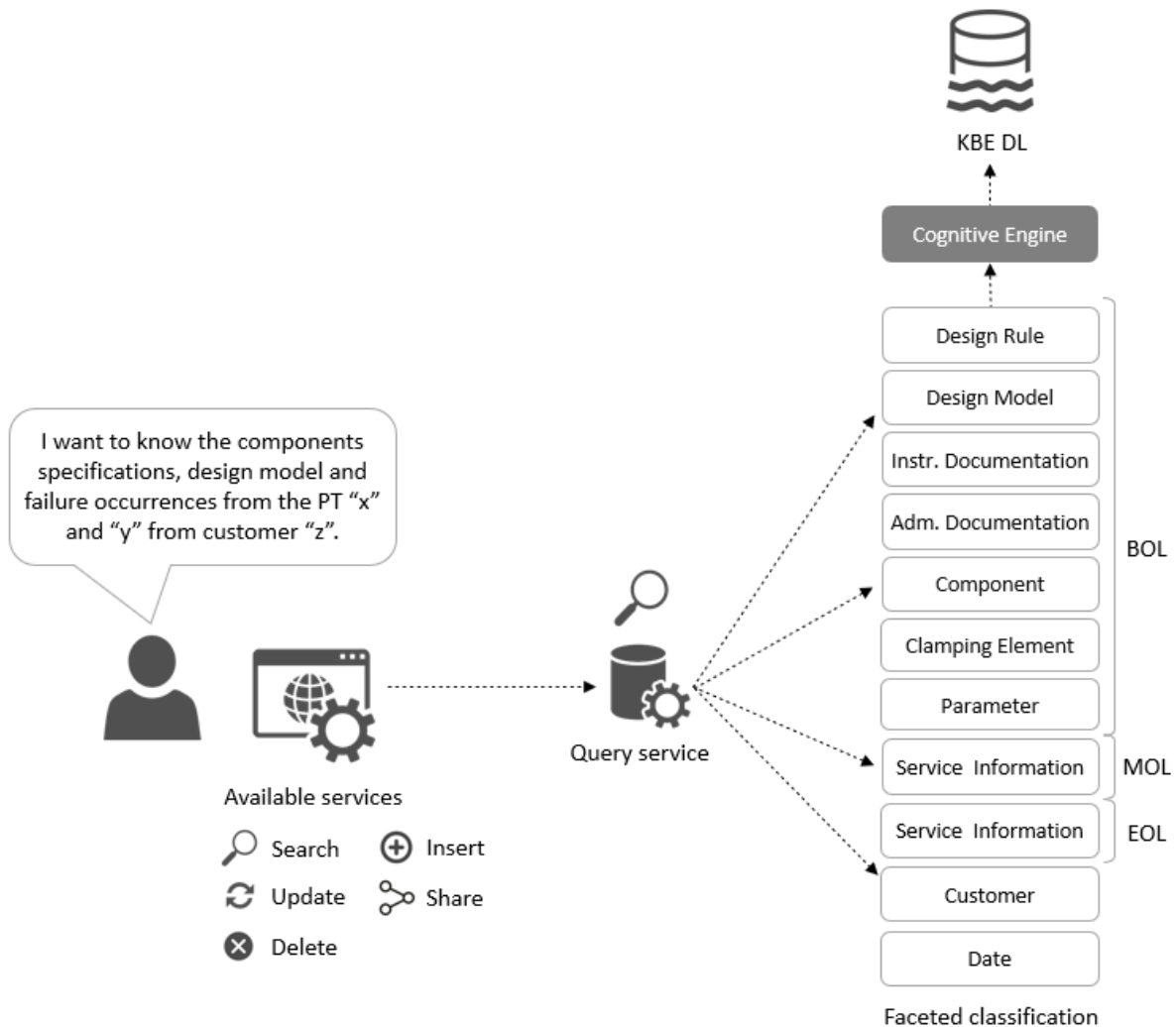


Figure 23 - Worker searching for information regarding PTs from a specific customer.

The IS then returns a package containing data, documents, meetings, email logs, and insights considered relevant by the ML and AI algorithms embedded into the CE to the worker's interests, as illustrated in figure 24. In this use case, the worker has at his disposal in a quick and unified way the resources needed to perform his tasks.

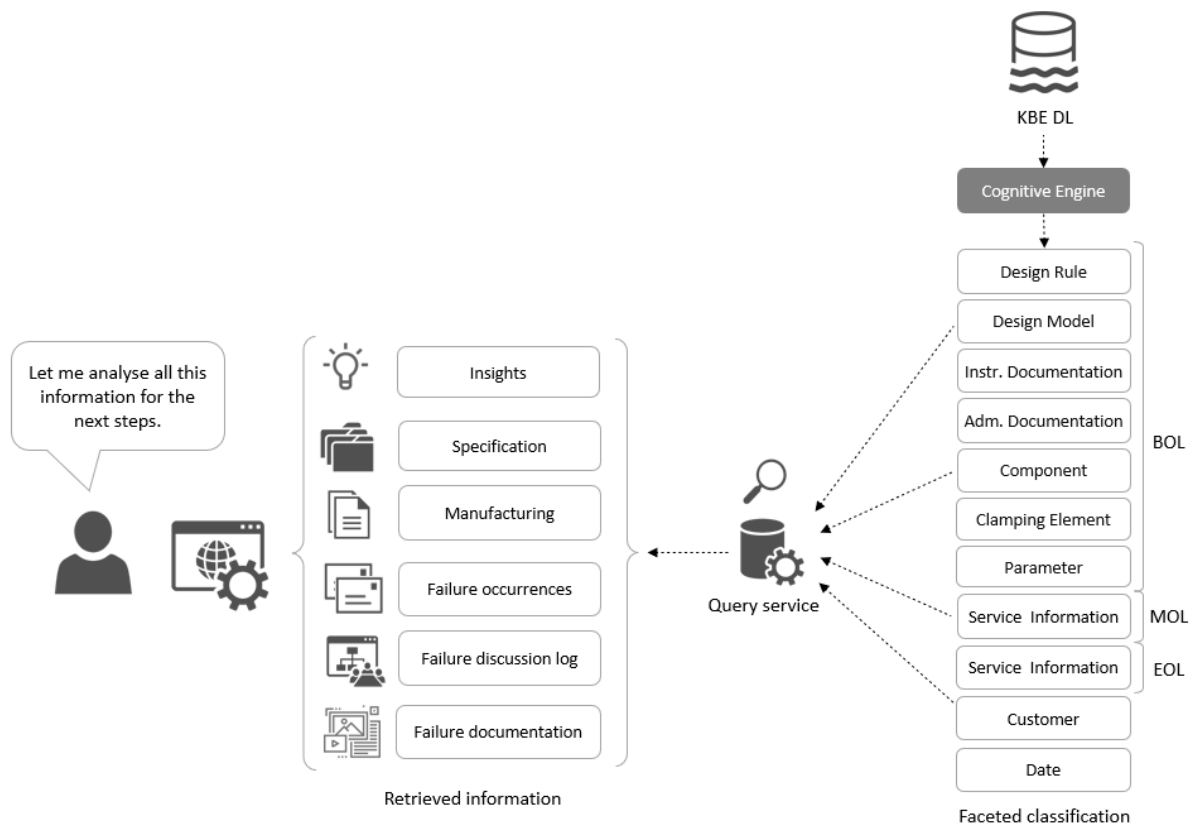


Figure 24 - Worker receiving the information package.

In the second use case illustrated in figure 25, the worker needs to update some data on specific stages of the PT's lifecycle. The worker inserts the updated data using the same IS and faceted classifications; the CE evaluates and stores the data into the KBE DL. The Date faceted classification offers the temporal context, so a comparison report showing the changes that have occurred is also created for versioning control. The sharing service is also activated and notifies the project stakeholders regarding the changes in the documentation.

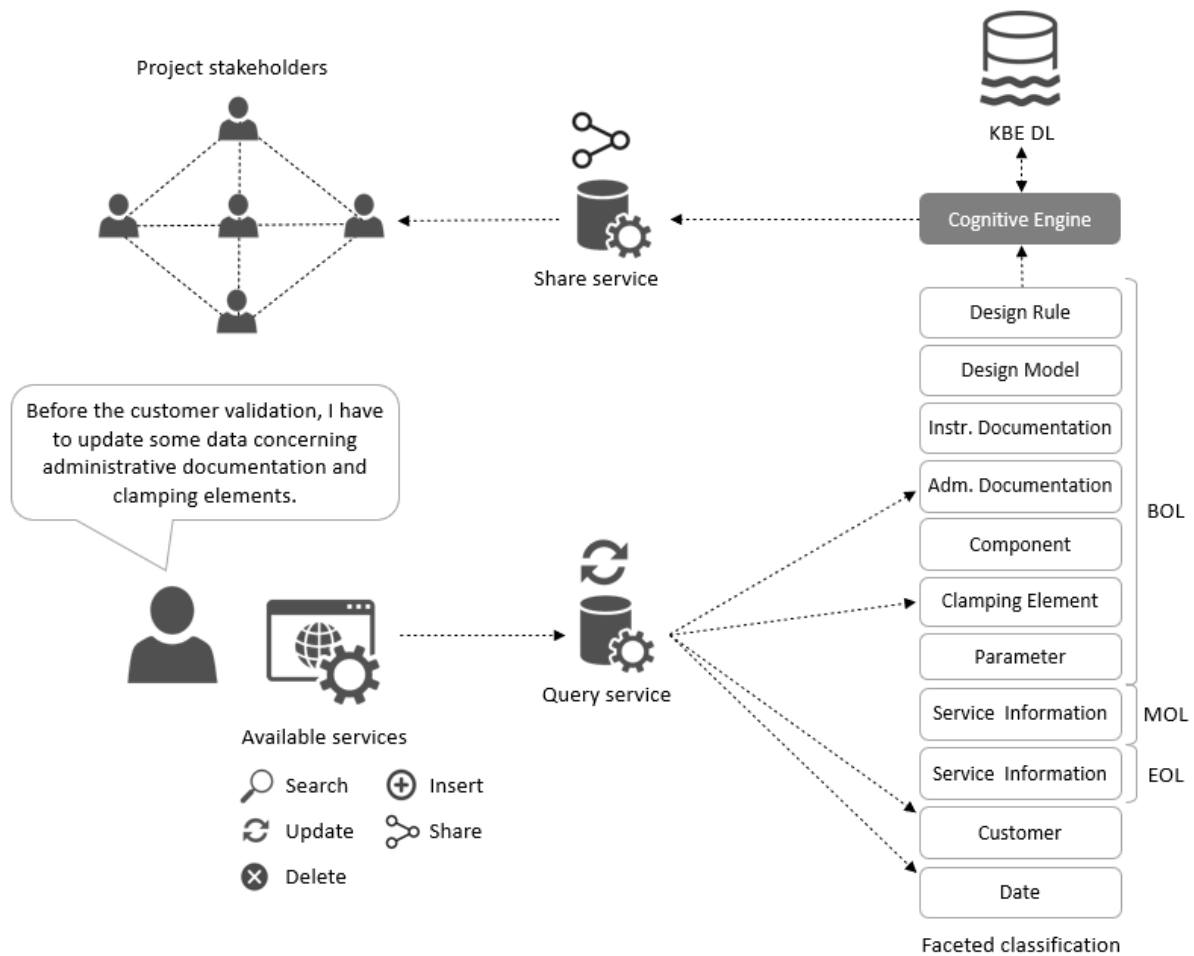


Figure 25 - Worker updating data for specific lifecycle stages.

Figure 26 shows how events' tacit and implicit knowledge is recorded and linked to the project. Once the events are over or executed, the CE evaluates the information, interacts with the faceted classifications and stores it into the KBE DL. The sharing system is also triggered to notify project stakeholders.

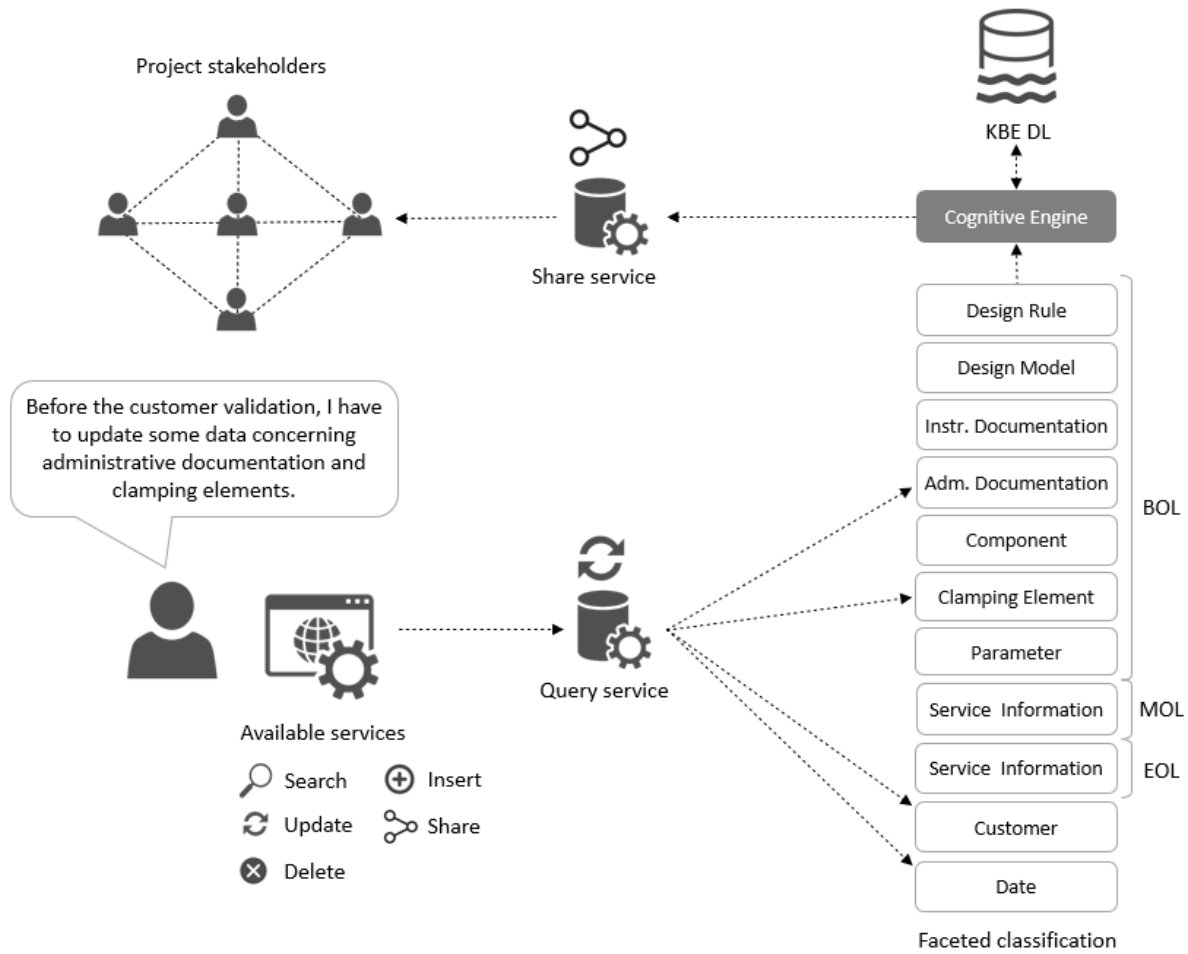


Figure 26 - Events updating data for specific lifecycle stages.

The following use case shows more of the project's requirements and role. In figure 27, the DT notifies a servicing worker of the status of a PT that may enter into a worrying state of operation. Using VR glasses, the worker checks the state of the DT that represents the physical PT. It is verified by the worker that there is a prediction calculated by the CE that a component will fail in a few days and that DT will trigger the maintenance service in advance.

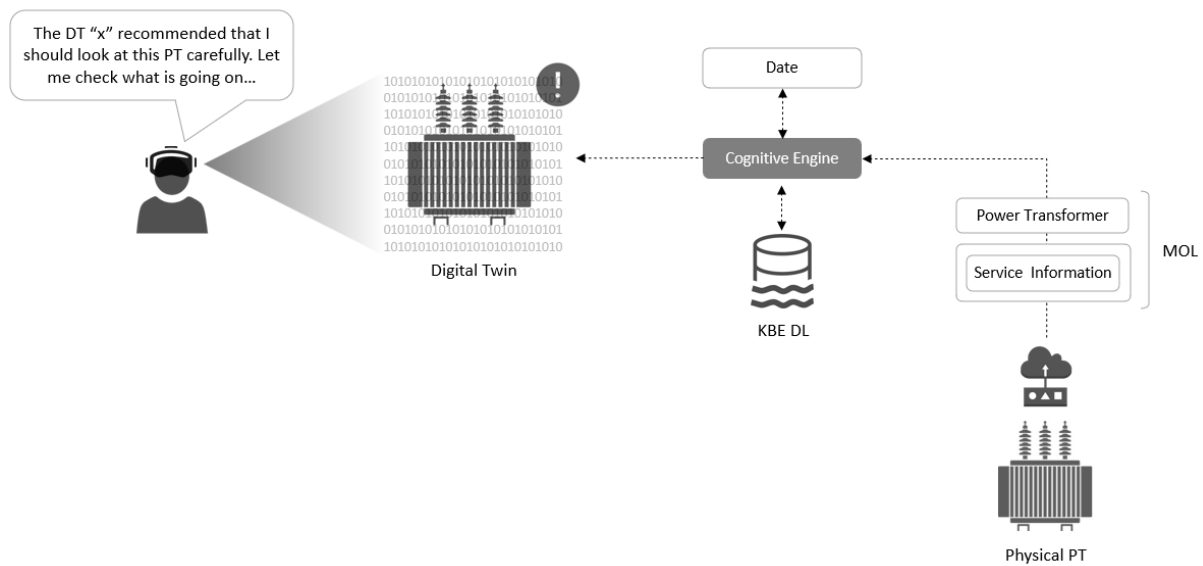


Figure 27 - DT failure detection and automatic maintenance schedule notification.

In figure 28, the notification is then disabled, and the worker can interact with the DT, checking the health index and components status. Also, new parameters can be configured. Further, the worker can discuss the best maintenance service strategy with the team in advance.

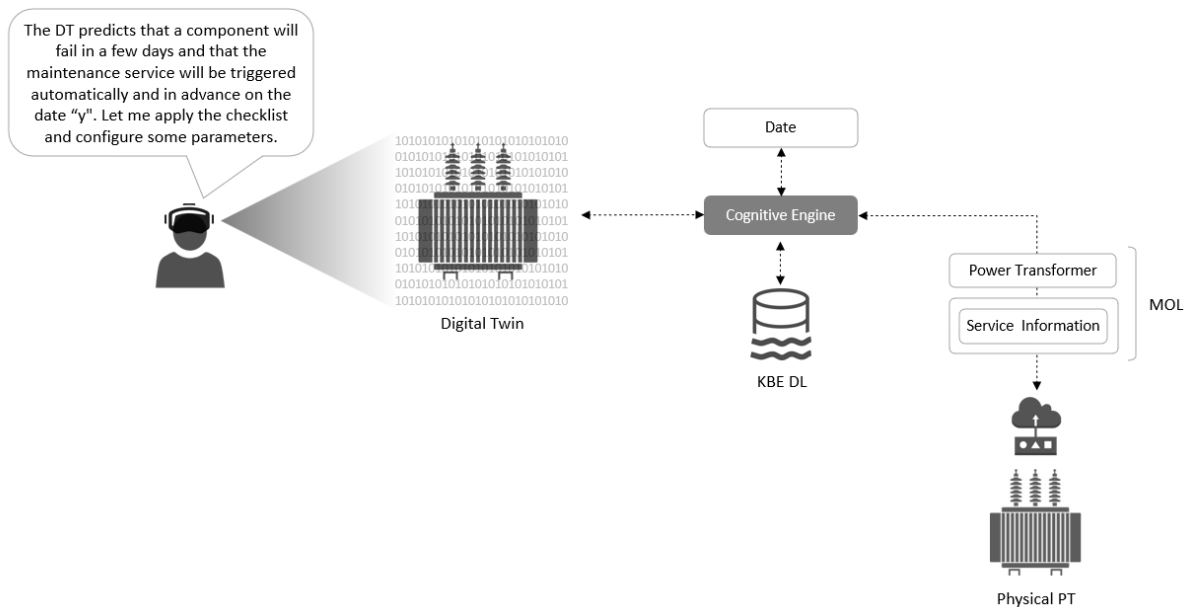


Figure 28 - Worker checking and interacting with the DT.

Just like in the first use case, it was not possible to deepen the research and obtain enough information during the fieldworking at Efacec to develop a POC.

These results were also supposed to achieve the specific objective of the dissertation, Obj1:

Develop a POC for a part of a process, including a knowledge lifecycle model, from data to knowledge, methods for collaboration fostering knowledge sharing, and new information/knowledge practices.

6.6. The impact on product design and engineering processes

When employed effectively, impact assessment can proactively handle risk and identify the future outcomes of the current or proposed action. Specifically, for the case study, the focus is to assess the impact on product design and engineering processes from the availability of data and information provided through DT.

To develop the project's key impact and related risks is necessary to compare the proposed state from the point of reference or the original condition.

For this, the first task is to revisit the KM and lifecycle requirements in appendices 4 and 5. These requirements are related individually to the impacts they can deliver. Being tactical impacts, they provide a baseline of the type of change in various contexts, from technical to cultural. Further, these KM and lifecycle impacts were summarised to formulate the project's key impact and risks.

Each impact has an identifier, the theme and subtheme, the impact description, and the related risk. Regarding the themes and subthemes, each requirement is organised into distinct topics, from addressing technical aspects of DT, such as data integration and analytics and lifecycle stage, to issues linked to changing the organisation's culture.

The criteria employed to formulate the key impacts were based on the importance and level of criticality noted in the internal TRF4.0 project documents and the emphasis identified for that factor in the research findings. The key impacts and related risks list are shown in appendix 6.

By examining the list, it is straightforward to observe how the impacts are interdependent and how, to a greater or lesser extent, the failure to implement any of them might interfere with the TRF4.0 project results.

These results are related to achieving the specific objective of the dissertation, Objo: Assess the impact on product design and engineering processes of the availability of data and information provided through the DT.

7. Conclusions

This chapter will conclude the work by summarising the key findings related to the question and specific objectives and discussing the value and contribution to the area. It will also review the limitations of the study and propose opportunities for future research.

7.1. Key findings

This dissertation research question to be answered was: How can a DT-based data and information architecture improve the PT design and engineering knowledge-based processes? In this regard, this work considered the PT developed by Efacec, and the background was the TRF4.0 project, which aims to digitalise the lifecycle of the PT.

The results suggested that the information and insights generated by DT through ML analytical methods could potentially optimise engineering processes and the LCM of the PT. However, there are significant challenges to TRF4.0 implementation, which will be discussed later in this topic.

The literature and application of the KBE in the industry are relatively mature, with some concrete results presented by authors such as Emberey et al. (2007), Van Der Elst and Van Tooren (2008) and Lin, Chan, and Wang (2008). The authors demonstrated the benefits of applying methods which significantly reduced production time and cost, one of the reasons for the existence of the TRF4.0 project.

On the other hand, the literature and application of DT are relatively recent, with approaches still very focused on the benefits and potential advantages that it can bring, especially on the CDT, which has a similar approach to that intended for Efacec's DT. In short, the development of the dissertation touched on contemporary themes and is still in a phase of maturation and experimentation. For this reason, this work is expected to contribute to developing the KBE and DT domains by presenting the organisation's current state and how the proposed improvements were built based on the research.

The research instruments used in the case study were sufficient and met the requirements for data collection. The natural challenge is the collection process that may be, to a greater or lesser extent, imbued with biases both of the respondents and the observer, but to the extent possible were possible to identify and circumvent without severely impacting the outcomes of the research.

The research results deepened and corroborated what was found in the initial phase of the project, which occurred before the beginning of this work and was dedicated to defining the

project's vision and the high-level requirements.

Under the specific objectives of the work, the first was to analyse the existing product design and engineering processes and point out a series of gaps and opportunities for the organisation to improve. Summarily it was possible to point out the following existing gaps.

The described KM challenges appear to create barriers that impact the entire PT's lifecycle and, consequently, the operation of DT if not overtaken. The company needs to dedicate efforts to solving this problem, as it is an essential enabler for the KM processes to be correctly implemented and the DT to deliver the expected results. Overcoming challenges such as the lack of data integration, information, documents, and IS operations could contribute to high-value stakeholders, take advantage of the available rich data and information, and spend time implementing authentic innovation practices

Regarding methods for tacit and implicit KM, the research showed that the respondents positively viewed implementing mentoring programs and tools, such as Q&A helpful. Improving existing Tutorials aggregating videos and audio to the text and up-to-date content was demanded; developing structured meetings with well-defined objectives and agenda were also required. Storing the knowledge generated in those events was considered essential. Once implemented, these tools could enrich the projects and help the teams acquire new knowledge that would probably be lost over time.

There is also room for improvement in the analytical processes, especially in the Engineering department. The organisation could adapt the good practices noted in other departments regarding analytical techniques for the benefit of the Engineering department and others, with the definition of KPIs that focus on measuring the efficiency of the execution of their processes and milestone achievement. The culture of KM and analytics would be strengthened to unify workers' vision and discourse around one strategy and strengthen senior management's commitment to the TRF4.0 project.

Implementing an analytical culture is especially necessary as the organisation's growth strategy in the international market is based on presenting innovative and quality products. In addition, the organisation aims to lead the digital transformation movement, facilitate the product's lifecycle, and develop KM strategies, enabling the organisation to create an environment where stakeholders share knowledge, collaborate, and make decisions efficiently.

Moreover, for this to happen, there needs to be as a background a structured strategy designed for the stakeholders to be able to think analytically, being able to interpret the insights and reports brought by ML and AI algorithms embedded into the CE, and also be able to formulate relevant business questions to the CE that will support their professional tasks. In support of

the empowerment of the analytical culture, the BSC concept should be extended to all workers to broaden the vision, showing that process optimisation, learning and customer satisfaction are essential vectors contributing to the organisation's results.

For the complete lifecycle, PLM software and processes implementation could contribute to the integrated view and management of the lifecycle of the PT. Moreover, IS supported by the CE to the engineering team could improve efficiency in the complete engineering processes. If not implemented, the engineering team will continue to face difficulties in managing requirements and the design of the PT until the use of the insights generated by the DT.

For the BOL stage, there is an opportunity to integrate the teams more closely in projects with a higher level of complexity. This approach could increase the circulation of information between the groups, create a culture of sharing and collaboration, and shortens the time until the PT reaches the MOL stage.

The DT's MOL predictions could offer faster and more precise forecasts for decision-making, such as failure prediction, maintenance schedule, service recommendation, and RUL estimation to the PT, among others. Furthermore, the DT's EOL predictions will contribute to the organisation being seen positively by internal and external stakeholders and reinforces its positioning in favour of sustainability. It would severely impact the project if the prediction features from these stages were not implemented since the core functionality concerns the DT's capacity to deliver insights and operate autonomously.

Establishing a data disclosure agreement, security requirements, and very restrictive DM would be necessary for those customers from industries more willing to share data. Customers acting in strategic areas for a country will not share their data for apparent reasons of state security.

The following results concern achieving the dissertation's specific objective of refining the DT data and IM model included in the DT digital platform to meet the requirements of the knowledge-based processes. A faceted classification scheme was proposed as a query mechanism that could permit information retrieval through a predetermined structure. The proposed facet classification could describe the information referring to the PT's lifecycle and other relevant information employed for PT improvement.

The proposed classifications intend that the queries carried out by humans or by automatic services could obtain flexibly information that relates several dimensions linked to not only the PT's lifecycle but also information that links the PT to the insights generated by the DT, suppliers, customers, competitors, external macro factors, document formats and date.

An integrated model was proposed to achieve the following dissertation's specific objective concerning characterising the creation and dissemination of knowledge obtained from AI tools that explore the data from the DT.

This model introduced the KBE DL and CE concepts and showed how they would be coupled in the model management. It is proposed by the model that all components should interact among themselves, being data-driven and providing constant optimisation in operation. The literature has already presented a similar model that includes interaction between all components.

The complete data, information and documents should be integrated, ensuring a single, integrated view of any project or customer. The information from one or more PTs at any stage of its lifecycle could be retrieved for analyses, updated, added or reused by any team member from the Transformer BU.

Beyond the data from PT's lifecycle, what is explicit is the presence of the data, documents, and reports from the external macro factors that impact the whole transformers industry. This external data meets one of the project's needs, which is to answer what new technology should be implemented by Efacec in the PT shortly, or even a current need to assess the external factors that will positively or negatively impact the whole industry.

Furthermore, with the external data, it will also be possible to compare PT's performance with competitors' products. The insights could be delivered to the teams and to the Knowledge-based systems and events to support the meetings, mentoring, Q&A, forum systems, and co-creation events with helpful information.

A POC for a part of a process, including a knowledge lifecycle model, from data to knowledge, methods for collaboration fostering knowledge sharing, and new information/knowledge practices, was envisaged to achieve the dissertation's specific objective. However, it was not possible to deepen the research and obtain enough information during the fieldworking at Efacec to develop a POC. At least it was possible to develop a use case that suggested some applications.

The use cases demonstrated how the workers could formulate business questions involving any subject concerning the PT's lifecycle stage. For instance, for engineering, the CE could offer insights concerning what could be changed in the design to improve technical and economic performance at the highest level possible.

Another possibility regarding information from suppliers regarding new component features that could help assess compatibility for a possible immediate PT design upgrade. Regarding customers, up-to-date business information aggregated with external information from economic factors regarding strategic countries to understand their current and future energy matrix could anticipate necessities and develop a more intelligent offer. Without that external data, answering those questions would be nearly impossible.

The CE is the instrument designed to answer these questions. The reply could be more restricted to a single subject or aggregated, covering a wide range of topics. More use cases could be developed, but it depends on deepening the ML capabilities. There are opportunities to improve and refine the model as several functional aspects are offered by the ML and were not considered or detailed.

In the following dissertation's specific objective regarding the requirements for redesigned knowledge processes leveraged in new data and information structures centred in the DT, two sets of requirements were created, one for the KM and another for the lifecycle. Each requirement has an impact, providing valuable information for the organisation to evaluate which requirements should be implemented and in what order. Implementation priorities were not suggested, as this is a function that the company may best perform, as implementation priority was not a question considered in the research method.

For high-level engineering process efficiency improvement to become a reality, the organisation should implement a CE-powered IS at certain milestones. A POC was envisaged, but just like in the first use case, it was not possible to deepen the research and obtain enough information during the fieldworking.

The use cases illustrate how the workers could interact with the CE-powered IS, retrieving, inserting and updating information. The use cases also demonstrated how the events for knowledge exchange and sharing would be evaluated by the CE and registered in the KBL DL.

One last use case addressed the interaction of a worker with the DT and how this interaction could impact the physical PT. The proposed use cases illustrated a small part of what is possible regarding interaction with the IS or what the DT can provide in terms of insights.

In common with all use cases, the facet classifications served as support so that the information handled by users and events could be assigned and integrated into the KBE DL and, when necessary, distributed to stakeholders.

Finally, to achieve the dissertation's last specific objective regarding assessing the impact on product design and engineering processes of the availability of data and information provided

through the DT, a key impacts and related risks list was developed.

It was developed mainly by summarising the KM and lifecycle requirements items and adding a risk associated with each one of the impacts. Similarly, requirements, impacts and risks were organised under themes; priority and order of implementation of the requirements were not considered.

By examining the list, it was straightforward to observe how the impacts are interdependent and how, to a greater or lesser extent, the failure to implement any of them might interfere with the TRF4.0 project results.

Riege (2005) has identified the many organisational, individual, and technological barriers to implementing KM. For TRF4.0, it is no different, even more so, considering that implementing KM processes is only one of the project tasks. As stated at the beginning of the section, there are significant challenges to implementing digital transformation.

These changes go beyond technology. They involve cultural changes in how the leadership and internal stakeholders think about the business. Even so, the organisation must be prepared to overcome the risks and achieve its objective of offering the best products in a highly competitive market.

7.2. Limitations of the research

Regarding limitations, observer bias was significant because the researcher conducted the interviews individually and not in a team of researchers. The team observation would enable comparison and confrontation of impressions to reduce bias (Yin 2008).

Sampling respondents for interviews was a barrier because the agenda of the respondents that the researcher initially intended to interview was restricted and incompatible with the research deadline. Although half of the respondents were from the engineering team and the others from other departments with intense interfaces with engineering processes, the unbalance of the respondents' hierarchical positions biased the perception and description of a given problem. The vision and interpretation of a given situation from an executive's perspective sometimes proved not comparable to that of a manager or coordinator.

Furthermore, the high hierarchical position of the respondents also contributed to the bias of some of the responses on more sensitive topics, which were coated in more political and neutral discourse.

This work did not discuss the technical details of data and application integration, nor the enabling technologies and their implementations of DT. Lastly, the research did not study DT

design from the STS-D perspective.

7.3. Future research

The research development perspectives should give continuity to the work developed in this dissertation. Future work will focus on the following three aspects.

Firstly, improve the research method when determining the sampling of interview respondents so that the answers provided are balanced and comparable. Furthermore, to reduce the observer bias by incorporating an investigation team and employing a quantitative approach, for instance, based on survey research, to obtain statistical verification of the proposals.

Secondly, from the technological perspective of the DT, deepen the studies on the use of Blockchain and its influence on Supply Chain Management (SCM), IoT networks, and IM. Study the implication and usefulness of the Metaverse in virtualising the DT ecosystem. Moreover, few successful implementation cases fully realise the vision of CDT. For this reason, more profound studies will be necessary to develop a complete understanding and incorporate cognitive capabilities into DT.

Lastly, incorporate the STS-D perspective to rethink how stakeholders interact and communicate. This approach can enable DT implementation outcomes to be better aligned with the organisation's strategic goals and objectives and help clarify what the DT can and should do to improve business performance.

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Appendices

Appendix 1 - Focus group full agenda and structure.

Knowledge platform status

Briefing of work done @ EFACEC

Within the scope of the TRF4.0 project, activities are planned that very briefly aim at:

- The characterisation at a macro level of the current state of the design processes of power transformers;
- The selection of parts of that process for a more careful analysis;
- The identification of improvement opportunities, based on Knowledge-Based Engineering approaches.

Therefore, following the meeting on 17h of December 2021, this meeting aims to:

- Macro exposition of the Design Process of power transformers;
- Exposure of the macro point of view of some elements of the engineering team (Daniela Duarte, Ricardo Guerra) involved in the main stages of the project;
- Several topics.

Knowledge Based Engineering

Macro processes and themes addressed

- Knowledge Management;
- Information Management;
- Collaboration;
- Action Plans.

Introduction for the participant

What is the purpose of this interview?

The present study is an integral part of the TRF4.0, T3.2 KBE Process Design project. In the context of requirements specification, the aim is to understand and characterise the maturity level of Knowledge Management in Power Transformer engineering processes.

What subjects will be covered in this interview?

The questionnaire is composed of groups of questions which address the following topics: Knowledge Management processes, management and promotion of explicit, implicit and tacit knowledge and analytical culture; technology issues at different levels, from Information Management to Information Systems; processes and Information Management in the Power Transformer lifecycle context.

How long is it going to take?

The interview is estimated to last about an hour.

Data confidentiality

All data collected will be used solely and exclusively for the TRF4.0 project and for academic purposes, with total anonymity and confidentiality of the information collected.

We appreciate your cooperation.

Questions

Position in the organisation

Question 1. How long have you worked at the organisation?

Question 2. Specify your area.

Knowledge Management Processes

Question 1. Has the organisation established a strategy and plan with well-defined objectives, processes, rules and goals for Knowledge Management?

Consider the following definition below to answer the following questions:

- Explicit knowledge is knowledge that has already been codified and stored somehow. It can be readily shared and accessed.

Question 2. Regarding the process of **STORING** data, information and electronic documents referring to a Power Transformer project, do you need to insert these elements in several unique or separate tools and repositories? Once inserted, are these elements connected or referenced to each other or not?

Question 3. Regarding the process of **RECOVERING** (searching and accessing) information about a project, do you need to access several tools and resources to collect electronic documents such as dossiers, guides, manuals, reports, multimedia, and information scattered in the repositories or is accessed through the centralised and integrated system?

Question 4. When starting a new project, is it possible to search the repositories for projects with similar characteristics, recognise these similarities and **REUSE**: data, information, knowledge and associated learnings such as specifications, manufacturing dossiers, scripts, operation reports and feedback from the customer among other elements of previous projects?

Question 5. When you need to SHARE data, information, electronic documents and multimedia of a project to your peers or even to other teams in the organisation: can you quickly execute the sharing process in a few steps, and in general, whoever receives it can access and consult the materials without, or with little, difficulty?

Question 6. Critical or essential information related to a project is constantly and permanently lost, which leads to rework to restore it?

Consider the following definitions below to answer the following questions:

- Tacit knowledge is our knowledge but is not aware of its existence. It is the knowledge that we acquire through practice at work, the experience achieved, the mistakes, and successes;
- Implicit knowledge is the knowledge we have that we can convey objectively; for example, a method for extracting data used day-by-day but is not yet documented.

Question 7. Consider the following instruments listed below and evaluate, first, if and then, how the organisation uses and applies each of them to promote knowledge:

- Mentoring programs to encourage senior workers to train juniors through classes, lectures and hands-on activities;
- Face-to-face or online meetings to discuss projects and inform workers about the characteristics, objectives and expected results, among other topics;
- Face-to-face or online meetings for case studies to share success stories, failures, and lessons learned with customers (debriefing);
- Face-to-face or online brainstorming for workers to present and discuss project ideas;
- Collaboration in the workplace, using collaborative suites like Trello, Basecamp and Teamwork.com for process tracking;
- Messengers such as Telegram and WhatsApp for recording informal discussions in the workplace;
- Discussion forums on an internal platform for workers to discuss problems, work processes, and opportunities;
- An e-mail with a discussion list for workers to discuss problems, work processes and opportunities;

- Question and Answer (Q&A) tools, for workers to post questions that their subject matter experts can answer. There, workers can search and get answers and best practices;
- Tutorials, in text format with videos and audios, so that workers can replicate more complex techniques and actions;
- The organisation has its proprietary developed tool for the specific purpose of Knowledge Management and uses it to manage tacit and implicit knowledge;
- The organisation uses third-party applications for the specific purpose of Knowledge Management to manage tacit and implicit knowledge.

Knowledge Management from the perspective of processes and analytical culture

Question 1. Does the organisation have a robust analytical culture, with very well-defined processes and a focus on constant monitoring and optimisation of the Business Unit's key performance indicators (KPIs) and the operation of the Power Transformer?

Question 2. Do dashboards with KPIs present the data you need without delays in updating information?

Question 3. Do these same Dashboards have an alarm and warning system so that it is possible to take action very quickly without harming the operation?

Question 4. Does the leadership hold periodic meetings to evaluate and analyse the Business Unit results and the performance of the Power Transformers, with very well-defined achievement goals?

Question 5. Does the leadership periodically develop action plans attributing responsibilities and deadlines to execute the suggested improvements and define goals to be accomplished?

Question 6. Are lessons learned after implementing the action plan recorded?

Question 7. In your activities, do you apply analytical methods such as predictive analysis, using Artificial Intelligence and Machine Learning to anticipate trends and make projections,

focusing on the optimisation and development of projects and preventing Power Transformer failures?

Technology-focused on Information Management

Question 1. Do you have all the data and indicators you need to efficiently execute activities related to engineering processes in the design of Power Transformers?

Question 2. How is it possible to qualify the data available to execute professional activities?

Instructions:

- For each pair of adjectives, there is a rating that best reflects the extent to which you perceive the adjective that best describes the available data;

Criterion	Positive bias	Negative bias
Availability	Available	Unavailable
Precision	Precise	Inaccurate
Relevance	Relevant	Irrelevant
Consistency	Consistent	Inconsistent
Completeness	Complete	Incomplete

Description of criteria:

- Availability: Data is available precisely when I need it;
- The data holds the necessary level of accuracy for decisions to be made without having to resort to other sources;
- Relevance: The available data are decisive, necessary, and relevant for the execution of my work;
- Consistency: The level of divergence of the same metric coming from different data sources and the compatibility of data from different databases;
- Completeness: The amount of data partially or entirely missing in a series.

Question 3. To obtain the needed information, processes of extraction, cleaning, transformation and calculation of the data are necessary until its final form is displayed in a report in a consolidated form. To what extent and proportion of manual processes do you carry out to consolidate this data compared to automated processes?

Question 4. What can you say about the estimated time you spend weekly in manual data processing and consolidation processes?

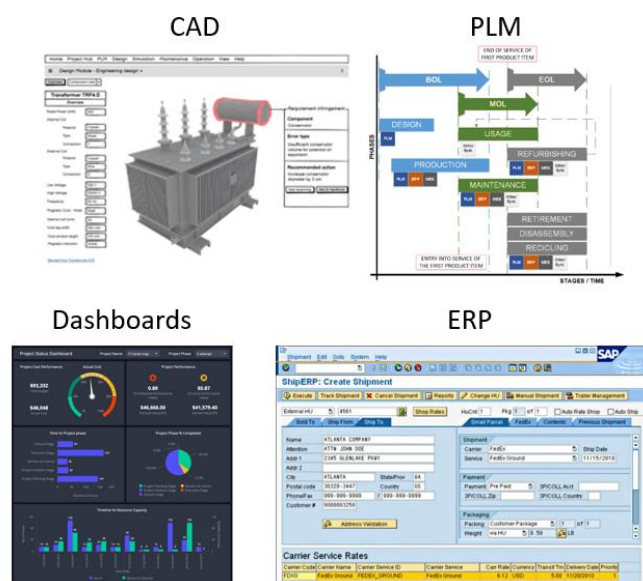
Question 5. Are the data provided by SUPPLIERS relevant to the activities you carry out? If yes, do you have complete, immediate and unrestricted access to their data, documents and other technological resources?

Question 6. Are the data provided by CUSTOMERS relevant to the activities you carry out? If yes, do you have complete, immediate and unrestricted access to their data, documents and other technological resources?

Technology-focused on applications, software and IT management

Question 1. Does senior management promptly implement changes in technology infrastructure to ensure the success of various projects or initiatives?

Questions 2. Consider the figure below an example of a typical set of tools, suites and technologies used by a large enterprise: Which suites, applications, and tools do you use most in your day-to-day professional?



Question 3. What is the level of integration of information and processes between legacy systems, suites, platforms and standalone applications?

Question 4. Do you have all the technological tools, software, and applications you need to execute activities related to the design of Power Transformers efficiently?

Question 5. Of the software and applications you use, how can you qualify them?

Instructions:

- For each pair of adjectives, there is a rating that best reflects the extent to which you perceive the adjective that best describes the available software;

Criterion	Positive bias	Negative bias
Speed	Fast	Slow
Flexibility	Rigid	Flexibility
Reliability	Reliable	Unreliable
Correctness	Correct	Incorrect
Updating	Updated	Outdated

Description of criteria:

- Speed: The tool's performance in performing the requested tasks;
- Flexibility: The software's ability to offer different configurations, report views, manipulation, and extraction of information according to the worker's needs;
- Reliability: The ability to perform tasks without failing and generating errors;
- Correctness: The ability to execute precisely the processes that were requested and correctly present the requested data;
- Update: The latest versions of software and applications are available.

Question 6. Do the tools, software, and applications allow you to easily view information, manipulate, edit and send reports and documents through your cell phone or other small-screen portable devices?

Engineering processes focused on the PT's lifecycle

Consider the following definitions below to answer the following questions:

- A product's lifecycle can be defined as a series of steps through which a product moves from design, production, and use to disposal. It can be divided into three main stages: Beginning-Of-Life (BOL), which includes the design and manufacturing stages, Middle-Of-Life (MOL), which includes the use, service and maintenance stages and End-Of-Life (EOL), where products are collected, disassembled, remanufactured, recycled, reused or discarded (Kiritsis, Bufardi, and Xirouchakis 2003).

Always consider this context, too, when answering the questions:

- Engineering processes can be impacted and improved through data and Information Management.

General lifecycle questions

Question 1. Does the organisation have a strategy, formal processes, and Power Transformer Lifecycle Management tools?

Question 2. Is historical data and information obtained throughout the whole lifecycle of Power Transformers available and analysed using analytical methods to add value to the product and services? If yes, what is this process's current state, and how can it be improved?

- Examples of possibilities and capabilities: optimising the performance of the Power Transformer to offer a more competitive product to the market; proposal and creation of new associated services.

Questions concerning the BOL stage

Question 3: Specifically on executing the following stages and the commercial area: commercial proposal, contractualisation, and design package. What can be improved to execute the design stage with greater efficiency and intelligence?

- Examples of possibilities and capabilities: more quickly configuration and validation of product development with the highest possible technical and economic performance; recovering and reusing similar projects delivered to the same customer or other customers with similar characteristics; accurately interpreting customer and market preferences at present and the trends of future technologies required.

Question 4. Specifically, what can be improved in the manufacturing and testing processes in operations and information flow so that this phase executes efficiently?

- Examples of possibilities and capabilities: can accurately predict lead times and costs based on previous work history for the same product type and business variables.

Questions regarding the MOL stage

Question 5. Consider the Power Transformer in operation at the customer and the critical data collected in real-time. This vital data: is it all present in dashboards, has the required update rate, and is it easily accessible to provide a scenario for quick decision-making when certain operating conditions are reached?

Question 6. Are there automated and intelligent processes for the Power Transformer to operate autonomously and adaptively to guarantee safety and efficiency? If yes, what is this process's current status, and how can it be improved?

Question 7. Does the transformer maintenance process have an intelligence component? If yes, what is this process's current state, and how can it be improved?

- Examples of possibilities and capabilities: it has recommendations for programmed preventive and predictive actions with the measurement of efficiency parameters of each component; risk management models for mitigating possible failures.

Question referring to the EOL stage

Question 8. Is there intelligent management of products and their components regarding the collection, remanufacturing, disassembly, recycling, reuse or disposal stage?

Conclusion

Do you have any additional comments you would like to add?

Final message

Thank you for your participation. Your valuable contribution to this study will be sincerely appreciated.

Appendix 3 - Engineering processes faceted classification

Engineering processes faceted classification		
Facet	Subfacet	Description
Design Rule	Normative Rule	Facet Describes documents that contain restrictive information regarding PT design Subfacets • Normative and Legislative Rules: originates from norms or laws; • Rules of Thumb: are elicited from the tacit knowledge of engineers; • Requirement: are agreed upon by the client and the organization based on client needs.
	Legislative Rule	
	Rule of Thumb	
	Requirement	
Design Model	Electric Circuit Model	Facet Describes models created during engineering design, and the models accurately represent the mechanical, electric circuit, and magnetic circuit properties of the PT Subfacets • Electric Circuit Model; • Magnetic Circuit Model; • Magnetic Circuit Model.
	Magnetic Circuit Model	
	Mechanical Model	
Instructional Documentation	Calculus Manual	Facet Employed to classify documents that contain information that helps engineers determine what, how or

	Project Manual	when to do a specific task during design processes Subfacets • Calculus Manual: guides engineers through the calculus process; • Project Manual: encompasses information related to the workflow of the transformer development process; • Software Manual: details how to use software related to PT design, such as CAD applications.
	Software Manual	
Administrative Documentation	Advanced Purchase List	Facet Describes documents that support the PT development process Subfacets • Advanced Purchase List; • Material Allocation List; • Transport Plan; • Type Plate; • Warehouse Booking List.
	Material Allocation List	
	Transport Plan	
	Type Plate	
	Warehouse Booking List	

Component	Active Component	Facet Details the PT component that a given document has information about Subfacets - Active Component: includes the subfacets Winding and Core; - Accessory: lists secondary components such as Oil Tank and Conservator.
	Accessory	
Clamping Element	Nail	Facet Refers to the devices or processes that support, divide, or connect PT components Subfacets This facet describes documents that contain information concerning: - Nails; - Nuts; - Reinforcements; - Washers; - Weldings; - Valves.
	Nut	
	Reinforcement	
	Valve	
	Washer	
	Welding	
Parameter	Dimension	Facet Describes documents that detail the properties of PT components Subfacets This facet describes documents that contain information concerning: - Dimensions; - Voltages;
	Voltage	
	Magnetic Energy	
	Mass	
	Material	
	Noise	

	Number of Coils	• Magnetic Energy; • Mass; • Material; • Noise; • Number of Coils; • Oil Level • Pressure • Temperature; • Vibration; • Shape.
	Oil Level	
	Pressure	
	Temperature	
	Vibration	
	Shape	
Service Information	Maintenance Record	Facet Describes information that originates from tasks executed on the PT during its operation or is created by the PT operation itself and information concerning how they were collected, disassembled, remanufactured, recycled, reused or discarded Subfacets • Maintenance record; • Malfunction record; • Sensor data; • Designation record.
	Malfunction Record	
	Sensor Data	
	Designation Record	
Lifecycle Phase	-	Facet Relates to the stage of PT's lifecycle in which the document or data was produced or captured, some possible values are: Contract, Specification, High-level diagram, Design model, Manufacture, Assembly, Test, Transport, Operation, Collect,

		Disassemble, Remanufacture, Recycle, Reuse or Discard
Customers	Contract	Facet Describes documents that contain information from customers related to engineering activities Subfacets • Contract: describes documents concerning product or services purchases or another commercial agreement; • Associated information: describes other documents provided by the customer for the engineering team.
	Associated Information	
Suppliers	Contract	Facet Describes documents that detail information from suppliers related to engineering activities Subfacets • Contract: describes documents concerning product or services purchases or another commercial agreement; • Products and Services: describes documents containing information regarding products and services catalogue; • Associated information: describes other documents provided by the supplier for the engineering team.
	Products and Services	
	Associated Information	

Competition	-	Facet Describes documents detailing competitors' information of interest to engineering and other areas related to the development of the PT
External macro factors	-	Facet Describes documents containing information of interest to engineering relating to factors impacting the entire transformer industry
Insight	Human Insight	Facet Describe documents that contain information that may improve or otherwise modify PT design Subfacets - Human Insight; - Automated Insight. The Human Insight and Automated Insight subfacets distinguish insights generated by the stakeholders or automatically created by software or algorithms
	Automated Insight	
Date	Year	Facet Describes various date formats required to establish a temporal reference to data, information, or documents
	Month	
	Day	Subfacets This facet encompasses the subfacets:

	Time (hh:mm:ss)	• Year; • Month; • Day; • Time (hh:mm:ss); • Day of Week;
	Day of Week	
Format	-	Facet Describes the format in which the document or data is presented. Some values considered are CSV, TXT, PDF, XLXS, PPT and Custom formats

Appendix 4 - Knowledge Management requirements.

Requirement ID	Theme / Subtheme	Requirement	Impact
KMo1	KM / Culture	The organisation should develop a more institutionalised KM strategy statement	Unites workers' vision and discourse around one strategy and strengthens senior management's commitment to the TRF4.0 project
KMo2	KM / Culture	The recognition for workers in terms of sharing and collaboration of information performance and employment of good KM practices should be implemented	Stimulates workers to collaborate with colleagues and accelerates the implementation of good KM practices throughout the organisation
KMo3	KM / Explicit knowledge	The process of storing, recovering and reusing data should be integrated	Reduce time spent in operating data across different applications and reduces the possibility of introducing to the system inconsistency, imprecision or missing data
KMo4	KM / Explicit knowledge	The electronic documents should be unified for versioning control	Prevents the evolution and previous version of documents from being lost

KMo5	KM / Tacit and implicit knowledge	A mentoring program should be implemented	Reduces the learning curve, brings experienced workers closer to novices, enhances collaboration and sharing of tacit and implicit knowledge
KMo6	KM / Tacit and implicit knowledge	A structured meeting process should be implemented	Provides optimisation of the event schedule, organises work and the produced knowledge
KMo7	KM / Tacit and implicit knowledge	An onboarding process for new members of a project should be implemented	Provides the reduction of the learning curve and distributes the knowledge of a project to all participants
KMo8	KM / Tacit and implicit knowledge	Q&A tools should be implemented, and tutorials should be improved	Enhances sharing and collaboration and enriches the project data or contributes to other subjects of interest for the organisation
KMo9	KM / Tacit and implicit knowledge	The knowledge generated from events such as meetings, and milestone e-mails, among others, should be stored and associated with projects	Contributes to the capturing and storing of tacit and implicit knowledge concerning a project

KM10	KM / Analytical culture	An analytical culture should be implemented across all departments	Contributes to a results-focused vision for everyone in the organisation and brings a sense of results achievement
KM11	KM / Analytical processes	Action plans and lessons learned should be developed with defined responsibilities and deadlines	Contributes to analytical and strategic thinking and contributes to the recording of lessons learned into the knowledge base
KM12	KM / Analytical processes	The BSC concept should be extended to all workers	Broaden the vision of the workers showing that process optimisation, learning and customer satisfaction are also essential vectors that contribute to the organisation's results
KM13	KM / Analytical processes	Interactive dashboards and a virtual model of the DTs should be available to the teams	Enable teams to quickly understand the status of a project and make quick decisions
KM14	KM / Analytical processes	The expertise in the analytical culture of the Commercial department should be shared abroad the organisation	Leverages an internalised culture can facilitate adoption by other departments

KM15	KM / IM	The entire data portfolio of the organisation concerning PT's lifecycle and external data should be integrated into a unique repository	Offers an integrated, unique and broader view of reality and reduces time spent in manual data consolidation processes
KM16	KM / IM	The data should be under a data quality processes	Provides reliability and reduces time spent on data correction processes
KM17	KM / IM	The data and information from suppliers and customers should be updated frequently	Reduces time spent on contacting stakeholders and provides the most up-to-date information relative to product upgrades from both sides
KM18	KM / IM	The data from external macro factors should be updated frequently	Provides strategic information to the Commercial department information concerning opportunities and threats to the transformers industry, allowing business anticipation
KM19	KM / IM	The data relative to competition should be updated frequently	Provides strategic information to the Commercial, R&D and Engineering departments on

			competitive movements allowing business anticipation
KM20	KM / Applications, software and IT management	Training should occur together with the reception of applications and software	Enables a faster learning curve and higher productivity
KM21	KM / Applications, software and IT management	The applications and software should be updated for the most up-to-date versions	Allows access to tools that are generally faster, more reliable, and more resourceful
KM22	KM / Applications, software and IT management	The applications and software operations, and interfaces should be integrated	Allows for a reduction in the time spent operating on platforms with different rules and interfaces
KM23	KM / Applications, software and IT management	The consumption of information should be more user-friendly on small-screen portable devices	Offers productivity for teams that depend heavily on information consumption outside the workstation
KM24	KM / Applications, software and IT management	The speed of the internal network should be increased	Prevents data, information and documents from being stored in temporary locations providing inconsistency throughout the IS

Appendix 5 - Lifecycle requirements.

Requirement ID	Theme / Subtheme	Requirement	Impact
LC01	Complete lifecycle / KM	The DT should be capable of offering knowledge extraction along the PT's lifecycle	Contributes to high-value stakeholders, take advantage of the available rich data and information, and spends time implementing authentic innovation practices
LC02	Complete lifecycle / Analytical processes	The DT should have a CE to deliver insights to and from the teams and IS	Offers a competitive advantage to the organisation since the optimisation will enhance PT design and operation, aggregating value to the product
LC03	Complete lifecycle / Analytical processes	The engineering team should have an integrated IS that quickly provides relevant and accurate information and insights from the CE via automated or ad-hoc queries	Improves efficiency in the complete engineering processes

LC04	Complete lifecycle / IM	The DT should be able to store information in various formats	Ensures that data in structured and unstructured formats will be integrated into the repository for later processing
LC05	Complete lifecycle / IM	The DT should provide a query mechanism to retrieve, insert, delete and update stored information	Ensures that data is managed with best practices and that integrity is maintained over time
LC06	Complete lifecycle / Applications, software and IT management	The organisation should implement PLM software and processes	Contributes to the integrated view and management of the lifecycle of the PT
LC07	BOL / Tacit and implicit knowledge	The organisation should integrate the teams more closely in projects with a higher level of complexity with the use of a personalised working model between Tendering, Commercial, Engineering and Project Management departments	Contributes to the homogeneous distribution of information to the team and promotes more collaboration between the participants during the requirements stage of the project

LC08	BOL / Analytical processes	The DT platform should be able to relate current PT specifications with historical designs and calculus methods to identify adequate calculus methods	Improves efficiency in the Commercial, Project Management and Engineering departments, allowing them to complete the specification based on historical data quickly
LC09	BOL / Analytical processes	Simulation tools should be integrated into the engineering design process	Improves efficiency in the engineering design processes and introduces the DT into the project
LC10	BOL / Analytical processes	The DT should identify nonconformities in PT design	Improves efficiency in the engineering design processes, suggesting corrections
LC11	MOL / Analytical processes	The DT should offer output visualisation based on meaningful performance metrics of PT	Contributes to teams quickly navigating and manipulating data for easy understanding of information and quick decision-making
LC12	MOL / Analytical processes	The DT platform should offer communication channels between its users, including managing alerts and notifications	Enables the quick decision-making over dangerous operations envelope, among other noticeable conditions

LC13	MOL / Analytical processes	The DT should optimise predictions by combining ML with physical models	Offers faster and more precise forecasts for decision-making
LC14	MOL / Analytical processes	The DT should apply a suitable ML model to predict system failures based on available data	Offers failure prediction and real-time fault detection to attain a new level of safety for both systems and users
LC15	MOL / Analytical processes	The DT should apply a suitable ML to update maintenance schedules based on operational data variations	Allows optimisation of maintenance resources and defines the components to be replaced and their life expectancy before failure
LC16	MOL / Analytical processes	The DT should apply a suitable ML to recommend new services or custom parts to a new customer	Enables intelligent cross-selling and upselling to increase corporate revenue and anticipates customer needs
LC17	MOL / Analytical processes	The DT should apply a suitable ML to recommend new services or custom parts to an existing customer	Enables intelligent cross-selling and upselling to increase corporate revenue and anticipates customer needs
LC18	MOL / Analytical processes	The DT should apply a suitable ML to estimate	Enables the PT replacement planning years ahead

		RUL based on available data	
LC19	MOL / Analytical processes	The DT should apply a suitable ML to recommend replacement/recycling of PT based on lifecycle predictions	Contributes to the planning of the destination of the PT and its components
LC20	MOL / IM	The organisation should sensitise customers to provide PT operation data	Allows the ML algorithms to offer more accurate and assertive results based on data acquired from diverse sources concerning location, environmental condition, design and operating conditions of the PT
LC21	MOL / IM	The DT should output real-time generated information through streaming	Ensures the most up-to-date data for decision-making
LC22	EOL / KM	When solicited, the organisation should inform and educate customers regarding what materials can be recyclable and what to do with them	Promotes collaboration with business partners and customers, advising them with relevant information
LC23	EOL / KM	The organisation should be prepared to	Contributes to the organisation being

		address relevant issues such as sustainability	seen positively by internal and external stakeholders and reinforces its positioning in favour of sustainability
LC24	EOL / Analytical processes	The DT should apply a suitable ML to recommend the collection, remanufacturing, disassembly, recycling, reuse or disposal of the PT	Promotes collaboration with business partners and customers, advising them to make the most optimal use of components

Appendix 6 - Key impacts and related risks.

Impact ID	Theme / Subtheme	Impact	Risks
IMPo1	KM / Culture	Institutionalised KM strategy statement Unites workers' vision and discourse around one strategy and strengthens senior management's commitment to the TRF4.0 project	If not implemented, the organisation will delay in implementing the digital transformation by not aligning workers under the same view, consequently not creating synergy
IMPo2	KM / Explicit knowledge	KM processes integration Reduce time spent in operating data across different applications and reduces the possibility of introducing to the system inconsistency, imprecision or missing data	If not fully implemented, the workers will continue not to work efficiently and continue to spend time in not aggregated value operations
IMPo3	KM / Tacit and implicit knowledge	Tacit and implicit KM The knowledge generated from events such as meetings, and milestone e-mails, among others, should be stored and linked to projects in the KBE DL; Required implementation and improvements	If not implemented, the DT will not take advantage of tacit and implicit knowledge from the workers, and collaboration and knowledge-sharing processes will continue to be underdeveloped in the organisational culture

		Mentoring program reduces the learning curve. Q&A, onboarding of new members process and more structured meetings enhance sharing and collaboration.	
IMPo4	KM / Analytical culture	Analytical culture implementation Contributes to a results-focused vision for everyone in the organisation and a sense of results achievement	If not implemented, the organisation will struggle to take advantage of all offered instruments, even implementing the DT and sophisticated methods such as ML
IMPo5	KM / IM	Information integration Offers an integrated, unique and broader view of reality; Data quality Provides reliability and reduces time spent on data correction processes.	If not fully implemented, the organisation will continue not operating efficiently and not taking advantage of the DT cognitive features
IMPo6	KM / Applications, software and IT management	Apps. and software integration Allows for a reduction in the time spent operating on platforms with different rules and interfaces	If not fully implemented, the workers will continue not to work efficiently and spend time in not aggregated value operations

IMPo7	Complete lifecycle / KM	PLM software and processes implementation Contributes to the integrated view and management of the lifecycle of the PT	If not implemented, the organisation will continue to face difficulties in seeing the lifecycle as a whole, preventing efficient management of PTs
IMPo8	Complete lifecycle / Analytical processes	A CE-powered DT Offers a competitive advantage to the organisation since the optimisation will enhance PT design and operation, aggregating value to the product	If not implemented, it will severely impact the project since the core functionality is concerned with the DT's capacity to deliver insights to all teams concerning the PT operation
IMPo9	Complete lifecycle / Analytical processes	Integrated IS supported by the CE to the engineering team Improve efficiency in the complete engineering processes	If not implemented, the engineering team will continue to face difficulties in the process of managing requirements, designing the PT and consumption of the insights generated by the DT
IMP10	BOL / Tacit and implicit knowledge	Team integration in projects with a higher level of complexity Contributes to the homogeneous distribution of information to the team and promotes	If not implemented, the teams will continue to execute the BOL process with less efficiency and collaboration and knowledge-sharing processes will continue

		collaboration and knowledge sharing	to be underdeveloped in the organisational culture
IMP11	BOL / Analytical processes	Nonconformities in PT design identification Improves efficiency in the engineering design processes, suggesting corrections	If not implemented, the engineering team will continue to face efficiency difficulties in the design processes
IMP12	MOL / Analytical processes	DT's MOL predictions Offer faster and more precise forecasts for decision-making, such as failure prediction, maintenance schedule, service recommendation, and RUL estimative, among others	If not implemented, it will severely impact the project since the core functionality is concerned with the DT's capacity to deliver predictions over PT operation
IMP13	MOL / IM	Data from PT operation Ensures that the data, information and documents acquired are as diverse as possible, allowing the ML algorithms to offer more accurate and assertive results	If not implemented, it will severely impact the project since the core functionality is concerned with the DT's capacity to ingest data from various sources to create the predictions
IMP14	EOL / Analytical processes	DT's EOL predictions Contribute to the organisation being seen positively by internal and	If not implemented, it will impact the project since the core functionality is

		external stakeholders and reinforce its positioning in favour of sustainability	concerned with the DT's capacity to deliver insights
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Annexes

Annex 1 - First workshop full agenda and structure. TRF4.0 consortium, internal document.

Agenda

14:30 - Welcome

Goals and structure of the workshop

14:40 - Efacec Organization; Digital Transformation and Market evolution

15:00 - Transformer 4.0 project overview

Introduction to the concepts of Knowledge-Based Engineering, Digitalization of Life-Cycle Management, Product-Service Systems (PSS), Additive Manufacturing, Sociotechnical systems in digitalization

15:30 - Group brainstorming session

- Group 1 - Knowledge-Based Engineering, Knowledge Aware, Knowledge Management
- Group 2 - Digitalization of Life-Cycle Management (LCM)
- Group 3 - Innovation in Product-Service Systems (PSS)
- Group 4 - Additive Manufacturing

16:30 - Coffee break

16:40 - Groups presentation of brainstorming results

17:20 - Wrap-up and end of the workshop

17:30 - End

Annex 2 - Second workshop full agenda and structure. TRF4.0 consortium, internal document.

Agenda

14:30 - Welcome

Goals and structure of the workshop

Overview of Workshop 1

14:35 - Introduction to the concepts of DT based KBE, DT based LCM, DT based PSS innovation and Additive Manufacturing (AM)

15:30 - Group brainstorming sessions

- Group 1 - Digital Twin (DT) and Knowledge-Based Engineering (KBE)
- Group 2 - Digital-Twin and Life-Cycle Management (LCM)
- Group 3 - Digital-Twin and Product-Service Systems (PSS)
- Group 4 - Digital-Twin and Additive Manufacturing (AM)

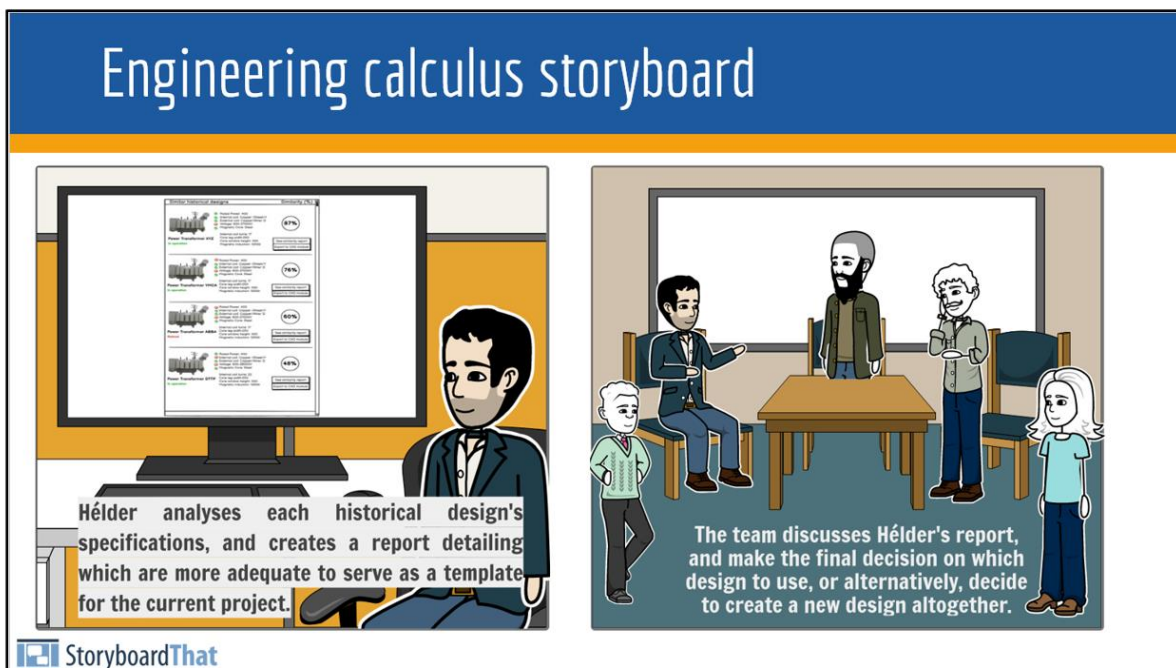
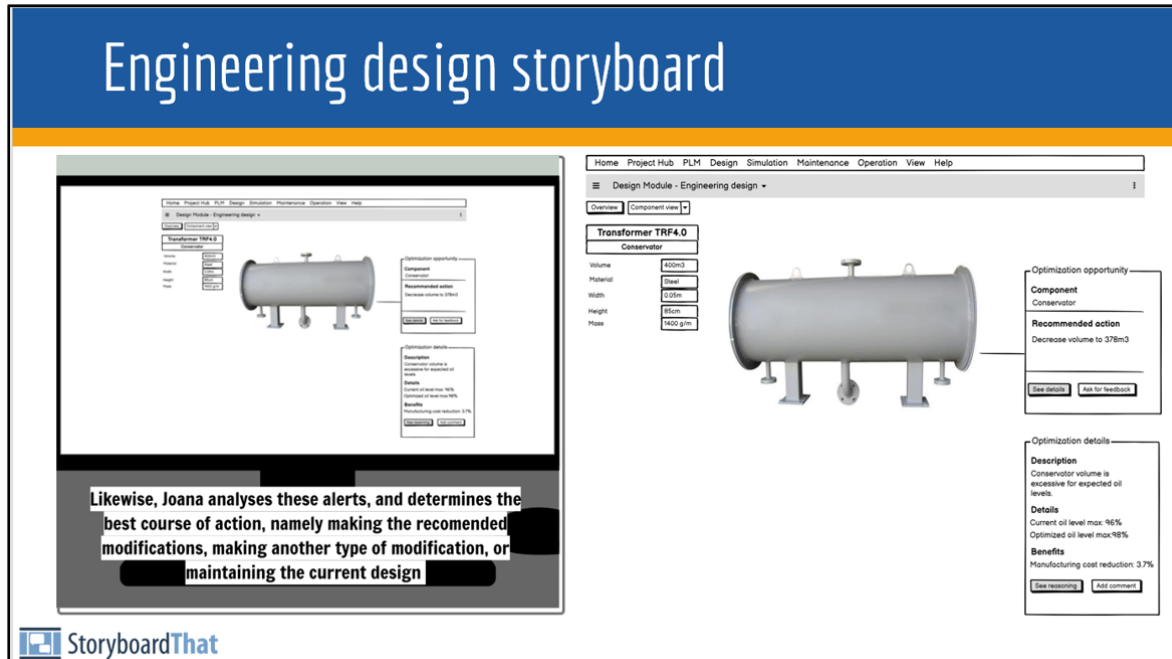
16:30 - Coffee break

16:40 - Groups presentation of the brainstorming results

17:20 - General discussion and next steps

17:45 - Wrap-up and end of the workshop

Annex 3 - User stories samples. TRF4.0 consortium, internal document.



Annex 4 - Focus group full agenda and structure for KBE concept. TRF4.0 consortium, internal document.

Agenda

TRF4.0 - Focus Group 1

"Knowledge-Based Engineering"

Date: 6 May 2021 (14:30-16:30)

Documents provided:

Target audience: Engineering department (8-10 p)

Goals: Elicit high-level requirements for the Digital Twin platform and services
To validate use case scenarios and identify new ones
To set up a detailed requirements elicitation plan (agile approach)

Agenda

14:30 - Welcome

Goals and structure of the session

14:45 - Discussion of the high-level requirements for the DT based KBE

15:30 - Use Case scenarios presentation and discussion

16:20 - Plan for detailed requirements

16:30 - End

Annex 5 - Focus group full agenda and structure for LCM concept. TRF4.0 consortium, internal document.

Agenda

TRF4.0 - Focus Group 2

"Life-cycle management"

Date: 9 June 2021 (14:00-16:00)

Documents provided:

Target audience: Maintenance, Service departments, Engineering department (8-10 p)

Goals: Elicit high-level requirements for the PT life-cycle management services

To identify use case scenarios

To set up a detailed requirements elicitation plan (agile approach)

Agenda

14:00 - Welcome

Goals and structure of the session

14:30 - Discussion of the high-level requirements for the DT based KBE

15:15 - Identification of use-cases for DT-based LCM

15:45 - Plan for the LCM work to be developed

16:00 - End

Annex 6 - Focus group full agenda and structure for PSS concept. TRF4.0 consortium, internal document.

Agenda

TRF4.0 - Focus Group 3

"Innovation in Product-Service Systems"

Date: 29 July 2021 (16:00-18:00)

Documents provided:

Target audience: Service department; Engineering department (8-10 p)

Goals: Elicit high-level requirements for the innovation in PSS services

To validate use case scenarios

To set up a detailed work plan (agile approach)

Agenda

16:00 - Welcome

Goals and structure of the session

16:10 - Efacec presentation on Servicing

16:20 - Discussion of the high-level for services enabling PSS innovation

17:10 - Use Case scenarios presentation and discussion

17:40 - Plan for the PSS work to be developed

18:00 - End

Annex 7 - Project requirement: documentation analysis. TRF4.0 consortium, internal document. TRF4.0 consortium, internal document.

T3.2 – KBE process design

Project requirements: documentation analysis

Annex 8 - First workshop summary of topics regarding KBE. TRF4.0 consortium, internal document.

Needs, challenges and opportunities. Business and technological context	Project benefits	The desired state to achieve, i.e., strategic impact
• Enhanced customer involvement; • Enhanced capability of analysis, storage, capture and distribution of data/information; • No reinventing the wheel; • Focus on continuous improvement; • Capture and storage of tacit/implicit knowledge; • Promote an actively engaged knowledge community; • More accessible knowledge; • Integration of various information: types, sources, formats; • Servitization.	• Enablement of a more extensive portfolio; • Enlarged service capabilities; • Foster of long-term acceptance of model-based/DT approach; • Capture and profit from tacit knowledge; • Retainment of knowledge from lessons learned; • Increased availability of knowledge; • Tools for easier automatization and systematization of knowledge; • More effective interaction between stakeholders; • Leverage of knowledge through Knowledge Aware practices.	• Knowledge reuse in engineering increased by 80%; • Recognition as a user of state-of-the-art knowledge technology and methods; • Fast generation of various design solutions; • Faster response through a quicker knowledge flow; • Reduction of lead time; • Model-centric approach to design and overall product lifecycle; • Increased profit of TRF BU; • An active and engaged knowledge community.

Annex 9 - First workshop summary of topics regarding LCM. TRF4.0 consortium, internal document.

Needs, challenges and opportunities. Business and technological context	Project benefits	The desired state to achieve, i.e., strategic impact
• A dynamic exploration of the product; • Management of components with different lifecycles; • Optimization of both design and manufacturing process; • Acquisition of data from various instances of the DT; • Maintenance improvement and optimization; • Network management possibilities.	• Optimization of the overall lifecycle; • The capability of network management through the PT; • Evaluation and prediction of the transformer's remaining lifespan; • Structuring of data and information from the development process; • Semantic interoperability with data from different sources.	• Model-based interaction with the help of a complete model of the device; • New services are developed based on the acquired data; • Optimization of manufacturing costs.

Annex 10 - Second workshop and focus group summary regarding KBE. TRF4.0 consortium, internal document.

Desired features and requirements of DT-based engineering. Design of the PT	Expected impacts on the PT engineering and design process	Needed competencies and infrastructures
• The integration of design models, e.g., simulation, structural; • A greater level of standardization with an increase in architectural references for future projects; • A lesser gap between simulated/design data and actual, measured data; • Greater interoperability between the data sources; • A faster information flow within the organization ecosystem; • The possibility to capture knowledge from all lifecycle phases, including the operational and disposal ones; • Greater regard for past lessons learned through the knowledge base.	Human perspective • Designers/engineers/colaborators information sharing and feel “safe” while doing so (avoidance in using knowledge as a survival tool within an organization); • Knowledge sharing between design roles; • The decrease in experience level required for the performance of design tasks in an autonomous way; • Improved communication efficiency; • Communication through nodes; • Enhancement of customer interaction through the use of DT and a model-based engineering approach.	Service perspective • AI-based tools capable of identifying design optimization opportunities; • Identification of design restrictions (manufacturing /legislation); • Providing customers with 3D PT models. Technological perspective • Model-based design; • Big Data analytics; • Infrastructure which enables the easy retrieval of historical knowledge; • Essential and comprehensive modelling competencies; • Extraction and organization of

	Technological perspective • Improvement of tool for product/service design; • Decrease of time spent on the retrieval of information; • Enablement of performing more design changes at later stages of the product lifecycle, when compared to a product ordered nowadays; • Retention of design knowledge in the future.	information/tacit knowledge.
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Annex 11 - Second workshop and focus group summary regarding LCM. TRF4.0 consortium, internal document.

Desired features and requirements of DT-based engineering. Design of the PT	Expected impacts on the PT engineering and design process	Needed competencies and infrastructures
• Online monitoring for status and RUL prediction for both customer and Efacec; • Determination of optimal use of transformer for lifespan boost; • Prediction and improvement of acoustic emissions.	• Reduction of the number of interruptions due to equipment failure; • Reduction of the number of non-scheduled maintenance operations, e.g., due to impending failure detected; • Evolution from purely descriptive analytics to cognitive analytics.	• Record, on top of measuring, both oil temperature and composition; • Transformer operation data. Currently, only customers have access to it; • Accelerometers would help with the monitoring; • Minor changes to the transformer design would need to be made to produce more data, e.g., to accommodate optic fibre technology; • More technology overall is needed to aid in data retrieval.