COLLABORATION AND KNOWLEDGE SHARING THROUGH TECHNICAL ARTEFACTS: THE DIGITAL TWIN AS BOUNDARY OBJECT

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Abstract: Digital twins have raised the attention of researchers and practitioners in a broad range of fields, from industry to medicine. The term refers to a virtual image of (cyber) physical systems used to represent and manage real-world assets. The model-based characteristics of digital twins and their widespread adoption make them a potential instrument for knowledge sharing from design to strategy formulation processes. This position paper develops theoretical possibilities for exploring the digital twin development and use as a boundary object. The paper starts by synthesising relevant literature about boundary objects as knowledge bridges. Then, it discusses the concepts and interpretations of the digital twin that will be used to argue that digital twins can be used as boundary objects. The resulting conceptualisation is promising and points to further research aiming at using digital twins as knowledge-sharing instruments.

Keywords: digital twin; boundary objects; knowledge sharing; collaboration.

Resumo: Os gémeos digitais têm despertado a atenção dos investigadores e profissionais numa vasta gama de domínios, da indústria à medicina. O termo refere-se a uma imagem virtual de sistemas (ciber)físicos utilizada para representar e gerir ativos do mundo real. As características de modelação dos gémeos digitais e a sua adoção generalizada fazem deles um instrumento potencial para a partilha de conhecimento, desde a conceção até aos processos de formulação de estratégias. Neste artigo desenvolvemos possibilidades teóricas para explorar o gémeo digital como objeto de fronteira. Começa-se por sintetizar a literatura relevante sobre objetos de fronteira atuando como pontes de conhecimento e discutir os conceitos e interpretações do gémeo digital. Em seguida argumenta-se que podem ser utilizados como objetos de fronteira. A concetualização resultante é promissora e abre caminho para investigar os gémeos digitais como instrumentos de partilha de conhecimentos.

Palavras-chave: gémeo digital; objetos de fronteira; partilha do conhecimento; colaboração.

Resumen: Los gemelos digitales han suscitado la atención de investigadores y profesionales de campos muy diversos, desde la industria a la medicina. El término hace referencia a una imagen virtual de sistemas (ciber)físicos utilizada para representar y gestionar activos del mundo real. Las características de modelación de los gemelos digitales y su adopción generalizada los convierten en un instrumento potencial para el intercambio de conocimientos desde el diseño hasta los procesos de formulación de estrategias. En esta ponencia se desarrollan posibilidades teóricas para explorar el uso de los gemelos digitales como objeto limite. Empecemos sintetizando la bibliografía pertinente sobre los objetos limite como puentes de conocimiento y se analizan los conceptos e interpretaciones del gemelo digital para argumentar que pueden utilizarse como objetos de frontera. La conceptualización resultante apunta a nuevas investigaciones encaminadas a utilizar los como instrumentos de intercambio de conocimientos.

Palabras-llave: gemelo digital; objetos limite; intercambio de conocimientos; colaboración.

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1 INTRODUCTION

The Digital Twin (DT) concept was initially proposed in 2002 as a conceptual model of product lifecycle management where a virtual entity represents a physical system, both structurally and behaviourally, with the physical and the virtual interconnected through a data link that synchronises their status. The DT provides opportunities for improved product lifecycle management and represents a significant change from the organisation's actual methods, processes, and tools.

The Digital Twin (DT) concept is widely recognised as a crucial technology within the industry. For example, in a recent report from 2021, Accenture positioned the DT as one of the top five strategic technology trends to watch. While the DT offers numerous possibilities for enhancing product lifecycle management, its adoption needs significant changes in an organisation’s current methods, processes, and tools. The DT promises to decrease the time and expenses associated with developing new products, maintaining existing ones, and facilitating swift innovation to seize emerging market prospects.

The diffusion of the DT concept and technology, particularly in the industrial sector, transforms it in an artefact that can support the exchange of ideas, information or ultimately, knowledge about product development and, consequently, its impact on other aspects of an organisation such the processes or even the digital transformation strategy. The central component of the DT is a digital representation or model of the physical system that is often used to discuss courses of action regarding the implementation of new products and processes. For example, designers often negotiate with model-based supports to do their reasoning. A model here is a generic concept that Carlile (2002) characterises as representations that can be observed and then used across different functional settings. They can be sketches, assembly drawings, mock-ups, computer simulations, etc., that depict or demonstrate current or possible solutions for problems that cross organisational functions and boundaries. This characterisation considers models not only as a means to compute the system’s behaviour but also as artefacts that can be useful for the organisational stakeholders to understand and interact with both products and processes, having thus some representational value (Panarotto, Bertoni, & Johansson, 2019) leading to technical knowledge sharing. Effective boundary objects do not need to be accurate to be useful (Star, 2010), as long as they enable people to share knowledge and find common grounds. As Star and Griesemer (1989) pointed out, boundary objects contain sufficient detail to be understandable by both parties, but at the same time, neither party understands the full context of use by the other.

Realising that the digital twin has not yet been studied as a boundary object in the scientific literature, we saw the opportunity to undertake exploratory research, given the digital twin's general (digital model) and specific (synchronisation, data processing) characteristics. In particular, the literature review of Camposano et al. (2021) identifies a cluster where the digital twin is viewed as "… a shared concern between different communities of practice" – as it helps practitioners in different industry domains to understand each other and work collaboratively. Our thesis is that if the digital twin is viewed as a boundary object, it can shed light on the role of this concept and technology in knowledge management and create helpful knowledge for designing information systems based on the digital twin.

To support our argumentation, we started by analysing three recent literature review papers dissecting the concept of DT from the theoretical lens proposed in the research of Carlile *et al.* about knowledge management and boundary objects. Then, we used the data and our own conclusions as participants observers from a research project aimed at digitalising a complex electrical device's life cycle in power grids – a power transformer. The case study is an engineering company in the energy and mobility sectors that produces this kind of devices.

This paper starts by synthesising the relevant literature on boundary objects, highlighting their role as knowledge bridges, then recent contributions on the conceptions of digital twin are described, and finally the argumentation of the digital twin as boundary object is presented. The conclusion points to possible research directions.

2 BOUNDARY OBJECTS AS KNOWLEDGE BRIDGES

Boundary objects are abstract or physical objects that can adapt to the needs and constraints of different parties using them while maintaining a common identity. They are loosely structured in general use but become more structured when used within specific contexts or tasks. These objects hold different meanings in various socio-technical contexts, yet they share enough structure to be recognised and act as a means of translation between different worlds. Objects, such as design drawings, maps, models, contracts, or learning materials, serve as boundary-crossing artefacts to facilitate cooperation while allowing diverse interpretations. They mediate interactions between different communities of practice (e.g., functional or departmental units), providing a common foundation for discussing problem-solving solutions.

By identifying points of agreement or shared references, boundary objects enable cooperative action without requiring individuals to abandon their unique perspectives and practices from their respective socio-technical worlds. They serve as bridges between intersecting social, cultural, and technical realms, fostering collaboration without necessitating a deep sharing of perspectives (Dodgson et al., 2007; Karsten et al., 2001; Nicolini et al., 2012; Star & Griesemer, 1989; Winter & Butler, 2011).

The fundamental aspects of boundary objects that enable them to play the role of knowledge bridges are interpretive flexibility, material/organisational structure, and scale/granularity (Leigh Star, 2010; Star & Griesemer, 1989). Interpretive flexibility confers a common point of reference for collaborative work between communities of practice. The general (or, to a certain extent, superficial, weakly structured) understanding of the structure and content of the object makes it possible to interpret it on similar grounds, useful to common work involving both communities. Each community, however, uses the object more detailedly in specific local activities (it becomes strongly structured), allowing to preserve the community's individual identity and work practices (Abraham, 2013; Star & Griesemer, 1989).

Carlile (2002) categorised boundary objects into four classes, building upon Star and Griesemer's (1989) original classification: repositories; standardised formats, methods or methodologies; physical prototypes and models; and maps. These categories have been interpreted differently according to the technical/scientific areas appropriating the boundary object concept. For example, *repositories* are places (e.g., databases) for uniform data, like measures or labels. *Standardised formats* are, for example, forms or templates, methods or methodologies like the ones used in software or mechanical engineering. *Prototypes, models,* and *maps* are the remaining categories frequently translated into physical, mathematical, simulation, or conceptual models, charts and maps (e.g., Gantt charts, process maps). In particular, objects in these two categories have the potential to facilitate cross-functional problem-solving, e.g. a consultant and her client discussing an operations simulation model or the strategy and the digital transformation teams using an enterprise reference architecture to develop a roadmap (Carlile, 2002; Rebentisch et al., 2022). The Digital Twin, either as a concept, an architecture or model, or as an implementation, falls into this category.

The boundary object is a valuable construct to understand and explore knowledge creation and sharing across organisational boundaries, whether functional, professional, or cultural. Carlile (2004) proposes three distinct types of knowledge boundaries that pose increasing challenges for crossing between organisational boundaries: syntactic, semantic, and pragmatic boundaries. Although Carlile associates syntactic boundaries with differences in the vocabulary used, which can be overcome by introducing a shared lexicon or common terminology, this type of boundary is better understood as the community-accepted ways of putting together the several instruments it uses, e.g. for problem-solving. To transcend semantic boundaries, in fact, also including differences in the use of vocabularies, the participating communities work together to find a common understanding by acknowledging their disparities and interdependencies. Lastly, pragmatic boundaries involve differences not only in meaning but also in interests. Each community has its own political agendas, and they perceive their knowledge as being "at stake". In this context, boundary objects play a crucial role in facilitating a negotiation process as the involved communities strive to find a mutually agreeable solution that serves their shared interests.

This influential research from Carlile on boundary objects and knowledge boundaries has been the basis for others to explore how normative models (e.g. enterprise architectures or reference architectures) can or cannot assume the role of “knowledge bridges” (Abraham, 2013; Rebentisch et al., 2022). In section 4, we further explore the boundary object concept applied to the digital twin, as a reference model, particularly in industrial organisations.

3 ARCHETYPES, METAPHORS AND CLUSTERS OF DIGITAL TWINS

The concept of DT was coined in 2003 in the field of Product Life Cycle Management (Grieves & Vickers, 2016) and initially referred to a holistic, digital engineering view from product design and development to production planning, production engineering, production, and associated services (Product Life cycle Management). Currently, the concept is receiving increasing attention from research and practice, even though its definition is also increasingly fuzzy. The DT is better understood as a concept system described by a network of related terms. The central concept characterising a DT is the *model*. A DT is, in the first place, a digital model of a physical asset (a product, a machine, a plant, etc.). A digital model of a physical asset must have a high degree of fidelity, thus carefully developed but continuously updated to reflect the physical entity it represents, comprising what is named a *digital shadow*. If the digital model can be changed according to e.g., business, operational or life cycle rules, and this is reflected in the physical entity (synchronisation physical-virtual), we are in the presence of a *digital twin*. This simple concept system, however, is far from providing a clear understanding of DT in theory and practice because layers of complexity have been added to generate more powerful digital twin concepts, such as *cognitive digital twins* (Adl, 2016). It is thus interesting to look at a couple of systematic reviews of the digital twin concept aiming to form a richer, high-level view of the concept.

Van der Valk et al. (2022) characterised “Digital Twin archetypes” based on a taxonomical analysis and morphological characteristics developed from a literature review and a qualitative analysis of experts' opinions. A simple conceptual model of a digital was derived, where the digital twin structurally consists of a digital representation, the data flow, the internal processing, and the internal repository. The entities interacting with the digital twin, besides the physical twin, include external data digital twin, historical data repositories, and external apps providing or consuming data from the digital twin. Departing from this conceptual model of digital twin, four archetypes were identified and characterised: *Basic Digital Twin* - adds a human-machine interface to the simple DT; *Enriched Digital Twin* - based on the basic DT, it enriches its database with pre-processed data from supplementary systems and provides semi-manual data acquisition; *Autonomous Control Twin* - it offers autonomous control, but at the same time, it contains a human-machine interface for the option to intervene, and as direct communication with another (virtual or physical) machine is possible, this archetype needs at least interoperability via a translator interface; *Enhanced Autonomous Control Twin* - it offers autonomous control over a physical asset while integrating external, downstream data processing systems; *Exhaustive Twin* - it offers exhaustive data acquisition options, data processing, and control over a physical asset and provides the user with all options; the twin can work and control autonomously but still humans have the ability to intervene or to enrich the database and, hence, provide a semi-manual data linkage; it demands a fully interoperable data linkage to downstream systems as well as to the physical asset itself.

Another approach to understanding digital twins was developed by Camposano et al. (2021), through a qualitative empirical case study, identified and characterised seven metaphors to define DTs. Although this research is specific to built assets, its results apply to the general DT concept. The resulting metaphors are the following: (i) "… a life cycle representation" – the DT mirrors all aspects of a physical asset over time; (ii) "… a process modelling method" – the DT allows modelling the industry or business process chain in which the physical asset is involved; (iii) "… a visualisation tool or UI" – the DT allows modelling complex or chaotic conditions of the asset through a visual digital abstraction; (iv) "… the convergence of the physical and digital worlds" – the DT and the physical twin can affect or act over each other like one single entity; (v) "… an IOT data platform" – the DT collects data about the physical asset from various sources to enable complex operations; (vi) "… a shared concern between different communities of practice" – the DT helps practitioners in different industry domains to understand each other and work collaboratively; (vii) "… a service ecosystem" – the DT integrates resources and capabilities from multiple independent actors to co-create value.

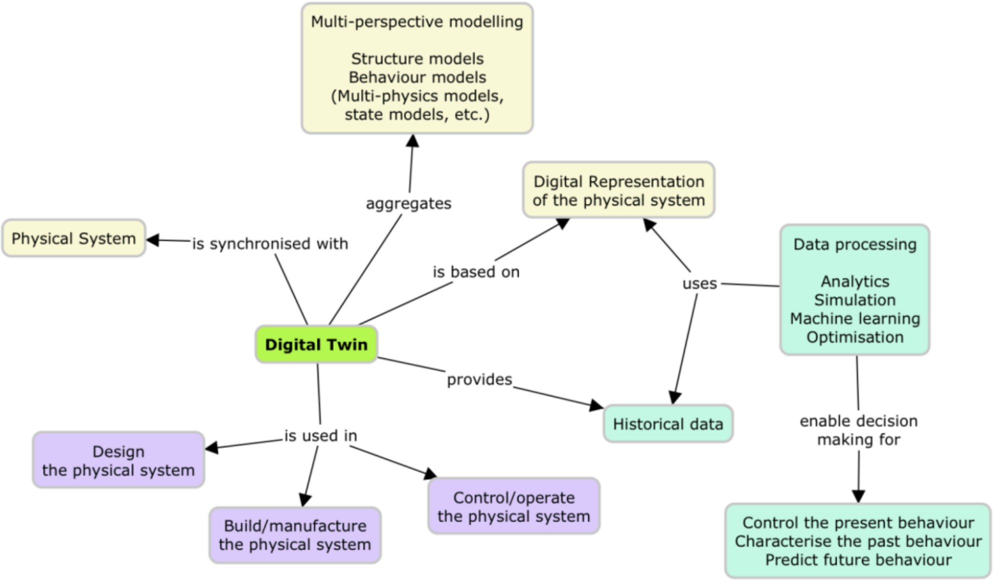
Finally, Semeraro et al. (2021) analysed the scientific literature on DTs up to 2020, being one of the results is the clustering of DTs definitions. *Cluster 1*, where the consideration of the life cycle phases is the core point in the definition of a Digital Twin*; Cluster 2* stresses the linkage between the physical system and the virtual model, actually representing cyber-physical systems; *Cluster 3* privileges the comprehensive representation of all data, information, and knowledge of the physical twin; *Cluster 4* focuses on the DT capabilities to simulate the multiple behavioural aspects of a physical system with a high degree of fidelity; *Cluster 5* virtual system enables the replication of the physical system into its “digital twin” throughout the entire value chain, by merging data into behaviour models.

4 DIGITAL TWINS AS BOUNDARY OBJECTS

We used a simplified theory abduction approach (Dubois & Gadde, 2002) to analyse the DT as a boundary object. Departing from the selected literature (see Section 1), we developed a concept map and identified the adequate set of boundary object properties to describe the digital twin (skeleton of the theory). Then, we used the data collected in the case study, mainly collected by us as participant observers, to show how the digital twin can act as a boundary object.

Cross-analysing the descriptions of the DT in section 3 and the boundary objects in section 2 we can identify three conceptual areas of the DT that can provide interpretive flexibility in collaborative work across organisational boundaries (see the three sets of concepts in different colours in Figure 1). The first set is related to the physical system life cycle (product, machine, asset, etc.). The DT can be used in the design, build, and operation phases, enabling a digital thread along these phases and fostering, e.g. Knowledge-based Engineering approaches (David, Jarvenpaa, & Lobov, 2021).

Figure 1 – Concept map of digital twin from the perspective of boundary objects



Fonte: Elaborado pelo autor.

The second set focuses on the modelling of the physical system. It includes the very core of the DT concept – the digital representation – but also calls for multiple perspectives modelling methods describing the expected structure and behaviour of the physical system. This set of concepts is relevant in helping interdisciplinary work for the design and engineering of the physical system (Azevedo, Tavares, & Soares, 2020). The third set of concepts relates to the data made available by the DT, apt to be processed by several techniques. This will support decision-making for controlling the present, characterising the past, and predicting the future behaviour of the physical system. Examples of boundary knowledge, in this case, are the interrelated activities performed by operations management and servicing in an organisation (Bertoni, Panarotto, & Larsson, 2016).

According to the classes of boundary objects defined in section 3 and the conceptual analysis above, the DT inherits characteristics of repositories, methods and maps. These categories were created by Star and Griesemer (1989) with the sole intention of broadly classifying artefacts that play the role of “knowledge bridges” in their study of knowledge borders in communities of practice. There wasn’t an intent of precision in that classification. For this analysis of the DT as a boundary object, we redefine the above categories to fit in the scientific and technical areas related to the DT. The basic DT involves the storage of data in the form of data streams or data sets. More evolved concepts of the DT also involve storage or access to technical documents and modelling information related to the physical system (Azevedo, Tavares & Soares, 2020). Different communities can then understand the DT as a repository of data and information related with the physical system. As the DT provides a view of the physical system life cycle phases, it provides an overall approach or method to design, build and operate the system. Finally, the DT is, above all interpretations, seen as a model (map) of the physical system, enabling the different communities of practice to share knowledge about the physical object.

We will now use the properties that Abraham (2013) synthesised in its literature review to continue arguing for the DT being considered a boundary object. These properties were recently used to analyse the role of reference architectures (an artefact conceptually similar in some way to DTs) as boundary objects in socio-technical design (Rebentisch et al., 2022). We briefly describe those now. *Modularity*: Boundary objects allow different communities to focus on specific aspects independently without interfering with others' use. *Abstraction*: They provide a common reference point on a high level of abstraction, eliminating local contingencies to highlight commonalities. *Concreteness*: Boundary objects address specific problems for different communities, allowing them to express their knowledge and learn about differences and dependencies. *Annotation*: Communities can enrich boundary objects with additional information to provide context for local use. *Versioning*: Changes in the boundary object can be traced chronologically, providing a history of changes and their rationale. *Shared Syntax*: A common schema of information elements ensures uniform use of information objects across communities. *Accessibility*: The boundary object is readily accessible to involved communities through appropriate communication channels and access rights. *Up-to-dateness*: The information in the boundary object is kept current, with timely communication of changes and updating processes. *Malleability*: Boundary objects are transformable to detect dependencies and negotiate solutions between communities. *Stability*: Despite local uses and annotations, boundary objects maintain a stable structure and provide a consistent reference frame. *Visualisation*: Boundary objects have graphical or physical representations, fostering dialogue and making them more accessible to different communities. In the same review paper, it is interesting to note some examples of concrete boundary objects taken from the analysed papers: software specification, timelines; technical drawings, machines; D-FMEA forms, CAD models, 3-D car models; simulation tools; electronic document library; project fact sheets, project plans. These examples are very much related to the DT field.

From the above properties, we hypothesise that *modularity*, *abstraction*, *concreteness* and *malleability* are the minimum relevant properties that can be used convincedly to describe the DT is a boundary object. We used the experience gained in a recently finished research project whose main goal was to develop a DT of a complex device used in power grids, the power transformer. The case study is an energy and mobility engineering company that functions across 65+ nations. Its global expansion hinges on introducing innovative, high-quality products, even if traditional, such as the Power Transformer (PT), an electrical apparatus employed in power grids. The departments responsible for PT development are organised in a matrix structure, where individuals with similar skills collaborate, leading to multiple managers due to shared work responsibilities.

Several departments were involved in the project, being the more relevant for this study the R&D department, product design and engineering department, and servicing department. The R&D department drove the case study in defining the general requirements for the power transformer DT (PT-DT). In this phase of the project, the stakeholders from the four departments were contributing to the vision and requirements of the PT-DT using an abstract understanding of the DT (abstraction) in three areas of impact (modularity): knowledge-based engineering and design, life-cycle management and innovation in product-service systems. Despite the more abstract shared understanding of the energy device fostered by the DT, it can be used to address specific problems in different departments (concreteness). While the product design and engineering department is devising how to use the data from operating PT-DTs and the resulting insights from data processing to improve and optimise certain design aspects, the servicing department is using the same data and other insights to devise how to create new data-driven services to increase the profitability and competitiveness of the product. During the visioning and requirements phase of the PT-DT, the different departments, together with the company's digital transformation office, debated how the PT-DT development could be used to trigger a broader digital transformation strategy, supporting the management of dependencies and negotiating solutions between departments (malleability).

This short analysis of the boundary objects' properties applied to the DT shows that it is feasible to use this theoretical lens to understand better the socio-technical nature of this concept and technology and that it can be operationalised as a knowledge-sharing artefact, particularly between organisational units or communities.

5 CONCLUSIONS

The potential of seeing the DT through the boundary objects lens is promising, both for research and practice. We have shown how the DT can be sufficiently abstract for a shared understanding and at the same time concrete for specific tasks by different departments, how it can be malleable to be adapted to different goals, and modular to focus on specific aspects of the tasks at hand.

Empirical research, specifically case study research, will be needed to create more knowledge about the different uses and contexts of the DT. Examples of research questions are "how to improve the digital strategy process through collaborative learning using the DT as a boundary object?"; "how to use the DT to improve the communication between departments in the product development process?". Also, from a systems engineering perspective, we can ask "what are the architectural properties of the DT that make it more likely to assume the role of boundary object?".

This paper describes exploratory research, resulting in a position paper regarding the potential role of the DT as an instrument for knowledge-sharing. Consequently, it has limitations: (i) the research design has only been outlined, (ii) the selection of the minimum set of properties to analyse the DT (the hypothesis) was not contrasted with different sets, and (iii) the data leading to the description of the DT properties as a boundary object was not described. This research is a work in process.

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