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The unique feature of designing with digital twin uncovered by design theory

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ABSTRACT: Digital Twins are widely recognized as a transformative technological trend, yet their potential to foster innovation, particularly their generative capabilities, remains underexplored. This paper investigates how they can transcend traditional optimization roles to serve as tools for advancing knowledge and generativity in the design of their physical counterparts. Leveraging C-K theory, a framework is presented for modeling design processes with Digital Twins, characterizing design scenarios and identifying two distinct forms of generativity. An illustration of these results shows how designers can leverage Digital Twin reflexive capacity to challenge and reconfigure underlying knowledge of their physical counterparts. The transformative value of this reflexivity, combined with remodeling capabilities, is highlights the exploration of new design pathway for Digital Twins themselves.

KEYWORDS: digital twin, C-K theory, design theory, design informatics, innovation

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1. Introduction

The emerging technology of the Digital Twin is of ten cited as a major technological trend (Nedic, 2019). Paradoxically, while using a Digital Twin seems innovative, the literature on its role in fostering innovation remains surprisingly inconclusive. By strongly emphasizing the connection between the real and the virtual, some studies limit the use of Digital Twins to exploring and optimizing its physical counterpart as it exists, framing it as a tool for incremental improvement (M. Liu et al., 2021). In contrast, others try to extend the role of Digital Twins to more innovative applications, by introducing the notion of 'Digital Twin Prototypes'; in which the virtual twin precedes the creation of its physical counterpart (Jones et al., 2020; Singh et al., 2021) or rethinking the mechanism connecting the real and virtual, thereby enabling the use of Digital Twins from the early stages of design (Jones et al., 2019). This debate raises the following questions: What is the potential of the Digital Twin to support designers to innovate? In particular, if its role is not confined to studying the known behaviors of the physical counterpart, then what influence does it have on the design process?

The literature review shows that this question crystallizes around the characterization of the generativity of Digital Twins. A first methodological contribution consists of proposing a model of a designer's action using a Digital Twin, based on C-K theory. This model makes it possible to describe and analyse heterogeneous design situations associated to a transformation project, highlighting two types of generativity: on the one hand, the inversion of a fixed model making it possible to optimise the behaviour of the physical counterpart at each change of state of the latter or of its environment; on the other hand, a mechanism for reformulating this model and restructuring the concepts associated with the transformation project. Finally, an example from the hospital sector is provided for illustration. This contribution provides a better understanding of how the Digital Twin differs from other design tools and also paves the way for a new type of Digital Twin that intrinsically integrates knowledge remodelling, thus offering a new perspective on their design.

2. Literature review

2.1. What is a digital twin?

The origin of the Digital Twin concept is generally attributed to Michael Grieves, who introduced it in 2002 during a conference on Product Lifecycle Management. At that time, he defined what he calls the 'Mirror Spaces Model', which consisted of three components: a physical space, a virtual space, and a data flow connecting them. By 2006, this concept evolved into the 'Information Mirroring Models', emphasizing the bidirectionality of the link between the two spaces and the multiplicity of virtual spaces associated with a single physical space (Singh et al., 2021). The term 'Digital Twin' appeared in 2010 in a NASA technology roadmap, linked to an earlier 'Physical Twin' project used in the Apollo program to simulate the behaviour of an object in operation. Subsequent technological advancements made this concept possible and helped democratize it, which then led various stakeholders to extend its application to other fields (X. Liu et al., 2023).

This enlargement has notably resulted in a diversification of interpretations of the concept, such that, at present, numerous literature reviews (Jones et al., 2020; Lim et al., 2020; M. Liu et al., 2021; Semeraro et al., 2021; VanDerHorn & Mahadevan, 2021) observe a lack of consensus on its definition. Three main characteristics emerge to distinguish the Digital Twin concept from that of models and simulations: the presence of a real/physical entity, a virtual representation of the physical entity, and a connection between the two.

The nature of this connection between real and virtual entities is particularly debated (VanDerHorn & Mahadevan, 2021; Wooley et al., 2023), raising more or less strict inclusion criteria. The most restrictive definitions—such as those requiring a bidirectional and synchronous connection—seem to be at odds with empirical uses. Indeed, none of the 120 so-called Digital Twin projects examined by Wooley (2023) in his systematic literature review meet this criterion. If this lack of a consolidated view can be interpreted as a risk of concept dilution (Jones et al., 2020), it also reflects its evolving nature alongside an increasing number of use cases (VanDerHorn & Mahadevan, 2021), suggesting the potential emergence of future forms of Digital Twins. Among them, different contributions to innovation processes could appear.

In order to avoid leaving out new interesting forms of Digital Twins, we use the definition proposed by VanDerHorn and Mahadevan (2021), which strives for inclusiveness:

> *"a virtual representation of a physical system (and its associated environment and processes) that is updated through the exchange of information between the physical and virtual systems."*

The notion of representation implies the presence of a model of the physical system, distinguishing the Digital Twin from the Cyber Physical System, which the latter lacks (X. Liu et al., 2023). However, like simulation, the model is just a constituent element of the Digital Twin, which is characterized by its instantiated nature (VanDerHorn & Mahadevan, 2021) and its ability to track the evolution of the physical entity over time, particularly at scales where its behavior can vary significantly from what could be anticipated (Wright & Davidson, 2020).

Thus, even though the concept of Digital Twin is currently widely debated, it is possible to identify its specific characteristics. This raises the question of how these interact with design practices.

2.2. Designing with a computer-based design tool

Previous research on other digital design tool can be a resource to better understand the role of Digital Twins as support to designers. Computational design tools can be classified into four categories (Bernal et al., 2015): (1) tools for generating solutions, such as parametric modeling, expert systems, generative design algorithms, and design languages; (2) tools for evaluating solutions, including performance evaluation and rules checking; (3) methods for decision-making, such as Choosing by Advantages and Collaborative Weight, Rate, and Calculate methods; and (4) tools for integrating processes, exemplified by Model-Based Systems Engineering (MBSE). The collaborative dimension of these tools, particularly for information sharing (Robertson & Radcliffe, 2009), is also emphasized.

The Digital Twin's multiple analysis capabilities using what if scenarios are often highlighted (Jones et al., 2019; VanDerHorn & Mahadevan, 2021; Vrabic et al., 2021), enabling it to be positioned as a solutions analysis tool. Additionally, they support decision-making by either providing recommendations or automating decisions (VanDerHorn & Mahadevan, 2021; Wilking, 2021; Wooley et al., 2023).

To the best of the authors' knowledge, its role as a tool for generating solutions is less debated in the literature. However, this characterization has already been carried out on other design tools around the notion of generativity. Bordas et al (2024) propose a classification of the generativity of design tasks into four types. On the one hand, those based on a fixed model linking design parameters (DPs) to functional requirements (FRs). These can be determined either by activation (FRs are deduced from DPs) or by inversion (DPs are deduced from FRs). On the other hand, types without a fixed model have a higher level of generativity. They can be distinguished according to whether they use a fixed language (where object dimensions are predefined) or not. The authors thus demonstrate that the Generative Artificial Intelligence algorithms under their study correspond to cases of design by inversion of a fixed model. Hatchuel et al (2021) develop a similar reasoning for Generative Design Tools, and describe its generativity as topological. These approaches draw heavily on design theories as a theoretical framework, enabling debates on the creativity of designers equipped with these tools. In particular, they help to explain why certain tools appear to generate creative solutions that are far removed from the solutions accessible without their use, but in fact conceal a new form of fixation (Lawson, 2002). Understand the action of the designer is also essential, including biases the tool can generate; such as premature fixation or restriction of the ideation to the tool's capabilities (Robertson & Radcliffe, 2009); and the way in which the knowledge and concepts embedded in the tool relate to field practices (Lawson, 2002).

The concept of generativity is therefore pivotal to understanding the role of Digital Twins in innovation processes. Analyzing these generative forms requires rigorous methods grounded in Design Theory to model the designer's interaction with the tool, as well as an understanding of its uses, an overview of which is provided in the literature.

2.3. What do the uses of digital twins reveal about their generative features?

The commonly used definitions of Digital Twins mainly focus on their components (Tomczyk & Van Der Valk, 2022) but rarely on the uses and users they are intended for (Camara Dit Pinto et al., 2024). The pursuit of ultra-realism and perfect fidelity, often emphasized, can lead one to believe that, once a perfectly accurate representation of its real counterpart is achieved, it would be adaptable to any purpose. This obscures the fact that the model is built from a specific set of questions (Lyytinen et al., 2023) that frame the knowledge one can have of the system (especially the description of its states) and the parameters that can be manipulated in the virtual realm.

Distinctions made in the literature to establish classes of Digital Twins can we a source to better understand the different conceptual scenarios that Digital Twins offer. The differentiations between these classes are based particularly on:

- the nature of information exchanges between the real and virtual (Hyre et al., 2022; Kritzinger et al., 2018; Pronost et al., 2021), which determines the respective autonomy levels of the machine and the user (Agrawal et al., 2023; Wilking, 2021);
- the characteristics of the physical entity, including the type of object (Lyytinen et al., 2023; Rantala et al., 2023; Singh et al., 2021), and the phases of its life cycle in which the Digital Twin intervenes (Jones et al., 2020; Lim et al., 2020; X. Liu et al., 2023);
- the degree to which the virtual representation comprehensively mirrors the real object (Singh et al., 2021);
- the type of tasks that can be performed by or with the Digital Twin (Fukawa & Rindfleisch, 2023; X. Liu et al., 2023; Semeraro et al., 2021). In particular, Liu (2023) distinguishes Design Phase Digital Twins, which allow for simulating and verifying the behavior of the future entity; especially to be able to manage uncertainties in requirements (Yang et al., 2022) or to integrate data from previous product generations over their entire lifecycle (Van Beek et al., 2023); from Operation Process Digital Twins, which predict the future state to improve situation assessment and decision-making, as well as from Dynamic Interaction Digital Twins, which enable direct interaction with the system and real-time optimization.

While many aspects may differ, a common pattern emerges: the virtual counterpart mirrors key characteristics of the physical entity and its environment, with certain aspects being continuously updated through data exchange. Simulation capabilities are then used to analyze multiple scenarios based on the system's current state, supporting informed decision-making. The definition of these scenarios, along

with the selection and implementation of the optimal one, depends on the nature of the interaction between the virtual and physical entities. According to the typology proposed by Bordas (2024), this corresponds to “design through fixed model inversion,” with various types of fixed parameters optimized for different inversion mechanisms. In this process, the underlying model remains unchanged, but the regular updating of the virtual entity makes the process highly repeatable. However, a pertinent question arises: Could higher levels of generativity be achieved by reintroducing motion into the model?
Lyytinen et al. (2023) offer a potential clue to unlocking a generative feature of this technology. They emphasize the constant endogenous change to which these systems are subject, questioning the feasibility of Digital Twins of organizations, in contrast to Digital Twins of things or business processes. The structure of the model may be too unstable to accurately represent reality. However, this gap between the model and the real system might also present an opportunity to better detect change and facilitate remodeling. This ability of Digital Twins to track system evolution over time — in ways that fixed models cannot — is further highlighted by Wright and Davidson (2020). Additionally, the literature explores methodologies to automate this adaptation (Erkoyuncu et al., 2020).
The literature thus makes it possible to anticipate two forms of generativity linked to the use of the Digital Twin. Firstly, the commonly described mode, which would correspond to an inversion of the underlying fixed model. Secondly, a mode with no fixed model, benefiting from the confrontation between the real and the virtual to enable reformulation. This lead us to the following question: How to describe the process of designing with Digital Twin and rigorously analyze the anticipated forms of generativity ?

3. Methodology : a C-K canonical model to characterize generativity

C-K theory, developed by Hatchuel and Weil, is acknowledged to be one of the most advanced formulation of a design theory (Hatchuel et al., 2018). It can be used independently of the object being designed, and has the advantage of allowing high levels of generativity to be described (Hatchuel et al., 2011). This methodology has already been used to track design methodologies (Kroll et al., 2014; Reich et al., 2012) and evaluate the generative regime of new technologies (Bordas et al., 2024; Hatchuel et al., 2021). Similarly, the tool’s place in the C and K spaces, its conditions of use, and the expansions it can produce in both spaces will be analysed to deduce its generative character.

4. Results

4.1. Designing with a digital twin: a model

Drawing on what we learned from the literature and mobilising C-K theory as a theorical framework, we propose modeling the creation of the Digital Twin of a real object or system R according to the following steps:

1. ***Prerequisites:***
   - ***Defining a transformation project for R:*** In generic terms this can be represented in C-K framework as the conception “ a better R”, which reveals the available knowledge about R as well as the meaning of “better” in the knowledge space K.
   - ***Identifying specific transformation opportunities:*** This involves generating sub-concepts of related to certain aspects of K(R) and K(better) and selecting one.
   - ***Identifying transformation project assessment criteria:*** This constitutes new knowledge, related to the privileged sub-concept.
2. ***Digital Twin design:***
   - ***Defining the Digital Twin state space based on the selected sub-concept i:*** This includes defining the R state variables $(X_1^{(i)}, \dots, X_N^{(i)})$ relevant to the project. These state variables can be split to identify variables that cannot be modified intentionally X_{env}, and variables that the user can control $X_{control}$.
   - ***Defining dimensions of interest:*** Relevant dimensions of “better” $(Y_1^{(i)}, \dots, Y_M^{(i)})$ have to be identified or designed. It may include state variables at future times.
   - ***Modelling the behaviour of the Physical Twin:*** $M^{(i)} : X^{(i)} \to Y^{(i)}$ can be built using a number of existing resources, including simulation tools.
   - ***Connecting the real and virtual systems:*** This connection provides access to measured data up to time $T\Big\{(\widehat{X}_1^{(i)}, \dots, \widehat{X}_N^{(i)})_t\}_{t \leq T}$.

3. ***Digital Twin operating cycles - Design with the Digital Twin:***
    - ***Generating new knowledge through the Digital Twin:*** The set of achievable outputs given the exogenous parameters $\{\widetilde{Y} \mid \widehat{X}^{t}_{env}\}$ is generated, expanding K.
    - ***Identifying states of interest among generated states:*** The project's assessment criteria enable to identify desirable situations, and to trace them back to the control parameters $X_{control}$ needed to achieve them.

   This cycle can be repeated when new data $(\widehat{X}_1^{(i)}, \ldots, \widehat{X}_N^{(i)})_{T+1}$ is added.

This first part of the process is depicted within the C-K framework in Figure 1 and corresponds to cases commonly described in the literature. When a significant gap arises between generated and measured data, a second design pathway emerges, leveraging this discrepancy.

4. ***Digital Twin redesign:***
    - ***Initial knowledge expansion:*** By comparing generated and measured data, it becomes possible to re-evaluate the model, and rediscuss initial knowledge about R and 'better'.
    - ***Regenerating initial concepts:*** This analysis can lead to a deeper transformation, prompting a redefinition of the concept and restructuring the concept tree, effectively restarting the design process.

This second part of the process is shown in Figure 2.

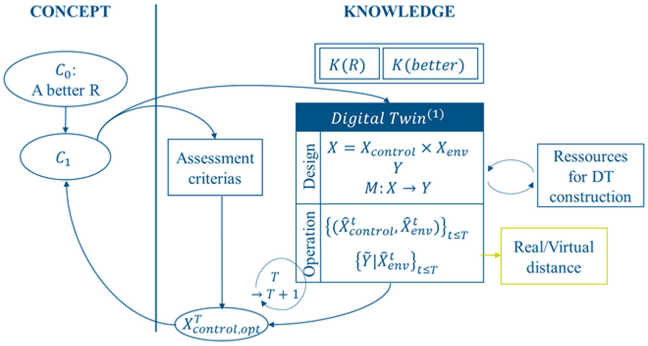

Figure 1. Transformation project, design and operation of the Digital Twin

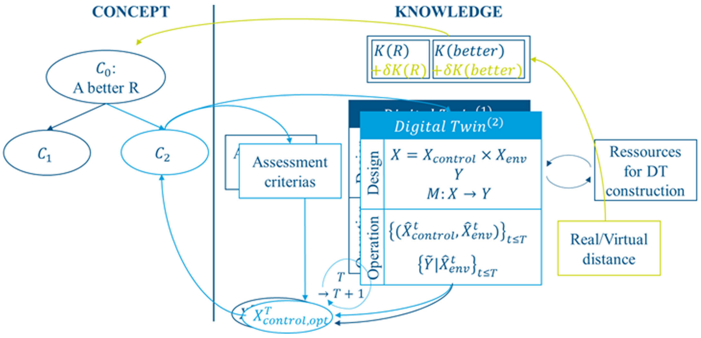

Figure 2. Regeneration of the initial concept by creating new knowledge about R and "better"

4.2. Implications : Characterizing two modes of generativity

The process of designing the Digital Twin presented here is evidently simplified and subject to variations. In particular, it should be noted that some approaches are primarily driven by the available data (Parmar et al., 2020). Nevertheless, it effectively enables the analysis of the conceptual situations described earlier, notably by referencing Liu's taxonomy (2023). The comparison of the cases is summarised in Table 1.

Thus, the different design cases described are distinguished by the nature of the data and parameters to be optimized, as well as by the nature of the inversion process applied – either left to the user after generating several cases, left to the user after identifying a group of interesting cases, or a unique solution selected by the Digital Twin itself.

Table 1. Comparison of the different classes of digital twins

	$X_{control}$	X_{env}	Y	*Optimisation method*	*Repetition*
Design phase DT -Yang et al. (2022)	Design parameters	Environment parameters	Design quantities of interest (from requirements)	Take into account uncertainty in environmental variables and requirements	When evolution of the specifications occurs
Design phase DT - van Beek et al. (2023)	Design parameters	Previous generations data + experimentations data	Product behaviour across manufacturing, service and disposal phases	Objective functions on the different phases of the lifecycle	With each new product generation
Operation Process DT - Liu (2023)	System parameters	Environmental parameters	$\widetilde{X}(t+1)$	Not specified, performed by the operator themselves	With each state change
Autonomous DT - Liu (2023)	Directly actionable parameters	Non-actionable parameters	$\widetilde{X}(t+1)$	Explicit (the DT should be able to choose a single solution)	With each state change

Stages 1 to 3 of the process described therefore correspond to the work mentioned in the literature and draws a first type of generativity based on the inversion of the underlying Digital Twin model. The connection between the real and the virtual makes this mode particularly repeatable with each change to the system, which is a first particularity of design with the Digital Twin.

Stage 4 of the model also reveals a second mode of generativity, with no fixed model, exploiting the learning effect on the distance between the real and the virtual. This acceleration of reflexivity regarding the underlying model seems to constitute a potential unique feature of the Digital Twin. It would nevertheless requires specifics capabilities, that is to say the ability to confronting virtual and real in order to generate new knowledge (including the capacity to distinguish unknown emergence from irreducible uncertainties), as well as the possibility to reconfigure the model at low cost.

An application of the proposed analytical framework is presented in the next section in order to illustrate its use and to highlight the types of generativity described.

4.3. Application: hospital digital twin for airbone risk prevention

The proposed illustration is the result of broader research conducted as part of a PhD thesis at a software company. This research focuses on various collaborative projects with hospitals, specifically in the development of Digital Twins, based on semi-structured interviews with project managers and the analysis of documents exchanged between the software company and the hospitals involved. The purpose of this communication is not to present the entire study, but rather to showcase one of the projects examined to illustrate theoretical findings.

The events described took place in the early stages of the project. The highly unfamiliar context was conducive to regular reconsideration of the initial hypotheses, in particular the software publisher's teams were critically examining the data provided, the models they were developing, and the needs expressed by the hospital. It was anticipated that the Digital Twin would be reconfigured through the efforts of the technical teams, who possessed all the necessary skills to modify it. Despite these limitations, we believe this example is valuable for imagining what the reflexive phenomenon described above might look like.

The project was initiated in the context of the COVID-19 crisis and aimed to help healthcare teams limit the risk of clusters in wards by simulating the spread of pathogens exhaled by patients depending on the positioning furniture of patients' rooms. The initial paradigm of the project is synthesis in figure 3 bellow.

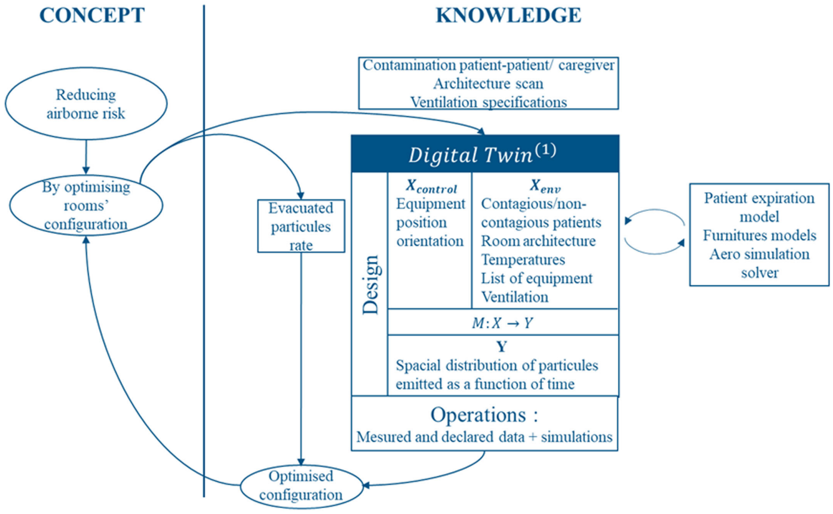

Figure 3. Project initial paradigm

Following an initial series of simulations, additional measurements were taken, revealing a significant discrepancy between the predictions and the actual distribution of emitted particles. Upon investigation, it became apparent that the actual behavior of the ventilation system differed substantially from the specifications, which surprised the hospital teams. As a result, the Digital Twin was updated to reflect the measured ventilation rather than the theoretical one. New simulations demonstrated that this ventilation defect had a significant impact on the propagation of contaminated particles within the department. This allowed the hospital teams to realize that ventilation could also be a key design element in limiting the spread of airborne diseases. The development of expertise in ventilation then enabled the teams to consider additional criteria for effective ventilation design, such as energy consumption. It should also be noted that at every stage of the process, the technical knowledge gained from the previous Digital Twin was incorporated into the knowledge base of resources for Digital Twin construction, contributing to the development of the future version. This process is summarized in Figure 4.

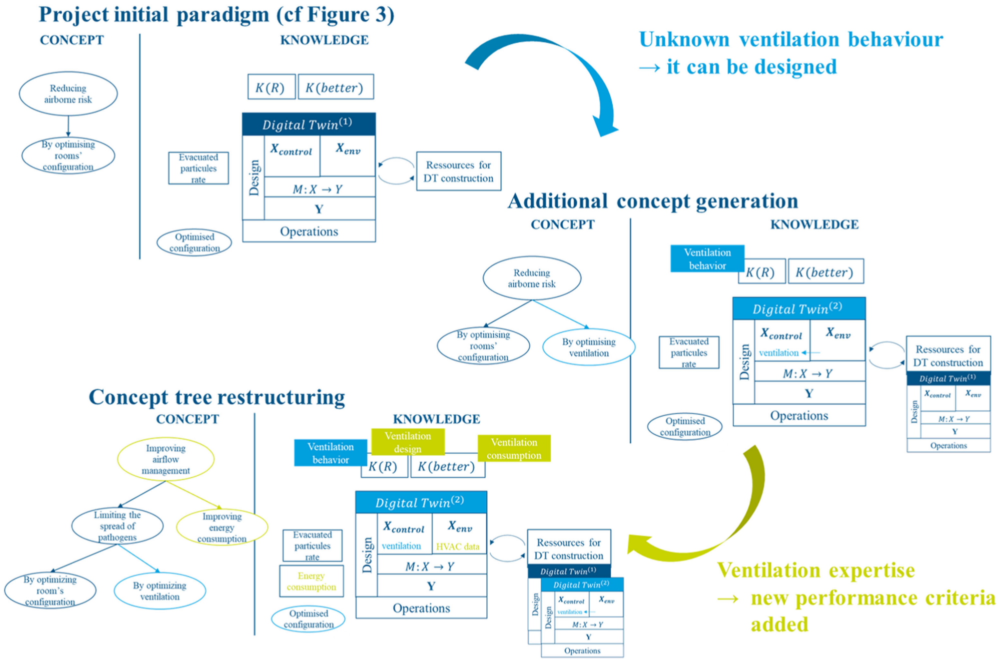

Figure 4. Expansion of knowledge and regeneration of successive concepts

5. Conclusion and discussion

At first glance, the characteristics of the Digital Twin may seem to hinder innovation processes by anchoring them too deeply in the situation "as it is". However, the introduction of a model of the designer's actions through a Digital Twin allows for a rigorous description of design situations, thereby clarifying how Digital Twins can support designers in their innovation efforts. Two types of generativity are thus identified.

Firstly, the model demonstrates a mode of generativity by inverting the fixed model underlying the Digital Twin, enabling the optimization of the physical counterpart's behavior whenever its state or environment changes. This mode aligns with situations commonly discussed in the literature. Additionally, it highlights the gap between the real and the virtual as a resource for questioning the model and, more deeply, the concepts associated with the transformation project, opening the way to a second mode of generativity, this time using a no fixed model.

An illustration of these mechanisms is provided, although it has its limitations, as it is framed more within the context of designing a Digital Twin rather than using one in the design process. Specifically, it is part of a broader context of market and technological exploration, meaning that the gap between the real and virtual is not the only driver for the restructuring of concepts and knowledge.

However, bringing unknowns to light by comparing the real and virtual systems remains essential even for established Digital Twins. As they track the behavior of the physical system over time, they reflect its transformations and foster reflexivity on the explicit knowledge surrounding them. This reflexivity—whose conditions require further analysis—enables Digital Twins to transcend mere reflections of their physical counterparts. A key challenge is distinguishing the emergence of the unknown from the inevitable uncertainty induced by modeling. The accumulation of knowledge, including insights into the real-virtual distance, enables the generation of new Digital Twins. The question of designing with the Digital Twin is therefore strongly coupled with that of its design, which must be flexible enough to evolve. Treating Digital Twins as fixed, turnkey solutions undermines their potential for generativity. Digital Twins solutions providers need to make reconfiguration accessible to those who are not technical experts to unlock their full potential.

These two characteristics—exploiting the gap between the real and the virtual and enabling reconfiguration—form the foundation for a more dynamic approach to Digital Twins. Whether this approach will lead to the evolution of the Digital Twin, or whether it will give rise to a new concept remains to be seen.

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