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Steering Representations—Towards a Critical Understanding of Digital Twins

Paulan Korenhof[1] · Vincent Blok[1] · Sanneke Kloppenburg[1]

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Abstract
Digital Twins are conceptualised in the academic technical discourse as real-time realistic digital representations of physical entities. Originating from product engineering, the Digital Twin quickly advanced into other fields, including the life sciences and earth sciences. Digital Twins are seen by the tech sector as the new promising tool for efficiency and optimisation, while governmental agencies see it as a fruitful means for improving decision-making to meet sustainability goals. A striking example of the latter is the European Commission who wishes to delegate a significant role to Digital Twins in addressing climate change and supporting Green Deal policy. As Digital Twins give rise to high expectations, ambitions, and are being entrusted important societal roles, it is crucial to critically reflect on the nature of Digital Twins. In this article, we therefore philosophically reflect on Digital Twins by critically analysing dominant conceptualisations, the assumptions underlying them, and their normative implications. We dissect the concept and argue that a Digital Twin does not merely fulfil the role of being a representation, but is in fact a steering technique used to direct a physical entity towards certain goals by means of multiple representations. Currently, this steering seems mainly fuelled by a reductionist approach focused on efficiency and optimisation. However, this is not the only direction from which a Digital Twin can be thought and, consequently, designed and deployed. We therefore set an agenda based on a critical understanding of Digital Twins that helps to draw out their beneficial potential, while addressing their potential issues.

Keywords Digital Twins · Representation · Technical discourse · Critical understanding · Philosophy

✉ Paulan Korenhof
research@korenhof.eu; paulan.korenhof@wur.nl

1 Wageningen University, Wageningen, the Netherlands

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1 Introduction

"Digital Twin". It may sound like a sci-fi movie by the Wachowski Sisters, but in fact it is the name of a new phenomenon in the world of technological innovation. Originating from product engineering, the concept "Digital Twin" is generally defined as a real-time realistic digital representation of a physical entity. Digital Twins of real-life entities are an emerging type of technology that is said to be able to "unveil dependencies between product, process, and operational characteristics that used to be hidden" (Schleich et al., 2017, p. 142), "uncover previously unknown issues before they become critical" (Glaessgen & Stargel, 2012, p. 7), predict future states and behaviour of their physical counterpart, as well as optimise their physical twin (see, e.g. Grieves & Vickers, 2017; Zhang et al., 2021a). Empowered by these promises, Digital Twins quickly advanced into other fields, like public management, economy, administrative sciences, life sciences, health science, environmental sciences, and even Earth systems sciences. The use of Digital Twins is seen by the tech sector as the new step-up for efficiency and optimisation, while governmental agencies and scholars seek to explore the societal benefits of Digital Twins in, for example city planning, democratic participation,[1] and addressing the grand challenge of climate change (see, e.g. Wan, 2019; European Commission 2020a, 2020b). Expectations of Digital Twins are especially skyrocketing as the EU seeks in its colossal project DestinE (Destination Earth) to build a Digital Twin of planet Earth in order to "test scenarios that would enable more sustainable development and support European environmental policies" (European Commission 2020b).

As Digital Twins give rise to high expectations and are being entrusted increasingly important societal roles, it is crucial to critically reflect on the nature of Digital Twins, their normative implications, and the feasibility of the ambitions that they are expected to realise. To date, however, a philosophical reflection on their nature is lacking. With this article, we make a start in filling this gap. Because no specific technology can be pointed out as the baseline for what identifies as a Digital Twin (Liu et al., 2020), we will focus our attention on Digital Twin conceptualisations in the contemporary technical academic discourse. These conceptualisations are important because they influence how Digital Twins are understood and employed. Digital Twins are increasingly used to represent not just products or objects, but living entities from the level of individual organisms to whole ecosystems. As such, they become a new means to generate knowledge in the life sciences and earth sciences and to manage and steer environmental challenges. This makes it crucial to critically reflect on the assumptions underlying the concept and its potential ambiguities.

Due to the societal relevance of Digital Twins in life sciences and Earth system sciences, in combination with the typical character of their physical twin (living organisms and ecosystems, but not necessarily human beings), we will focus in this article on what implications the dominant Digital Twin conceptualisation may entail in these particular fields. Moreover, we will maintain a focus on what a Digital Twin

[1] Hidalgo, C. *Augmented democracy*. https://www.peopledemocracy.com. Last accessed 12–07-2021.

is and does on a micro-level by exploring its concrete mechanisms. We will argue that the currently dominant conceptualisation of a Digital Twin as a realistic representation of a physical entity is problematic. Instead, a Digital Twin appears to be a technique used to steer a physical entity by means of representations. In current understandings of Digital Twins in the technical academic discourse, this steering seems mainly fuelled by a reductionist approach focused on efficiency and optimisation. However, this may not be the only direction from which a Digital Twin can be thought and, consequently, designed and deployed. Our analysis will result in a critical understanding of Digital Twins and provides a set of questions for future research on the use of Digital Twins.

The article is structured as follows: we start by critically exploring various descriptions of Digital Twins in contemporary technical academic discourse. We thereby identify a shared conceptual structure with a set of common traits. Next, we critically analyse the assumptions that underlie the current conceptualisation of Digital Twins against the backdrop of a wider philosophical perspective on the nature of technology and representation. We conclude by proposing a further research agenda that will advance a critical understanding of Digital Twins.

2 Digital Twin Conceptualisations

To identify the underlying assumptions in the Digital Twin conceptualisation, we first need to get a rough understanding of what the concept entails. However, extensive literature reviews by various researchers have shown that, so far, there is no uniform definition of what a "Digital Twin" is (Liu et al., 2020; Negri et al., 2017; Van der Valk et al., 2020; Wright & Davidson, 2020). In this section, we therefore analyse the conceptualisations as they appear in the technical academic discourse and look for structural traits. To this end, we focused on the top four most-cited and top three most recent articles on the topic across Web of Science, Scopus, and Google Scholar, and complemented this with articles frequently referred to in this initial selection, as well as the literature studies on the concept by Negri et al. (2017), Liu et al. (2020), Jones et al. (2020), and Verdouw et al. (2021). While the Digital Twin conceptualisations display a high variety in used terminology, we will show that they have a significant overlap in their main structure and traits.

An early and often cited Digital Twin conceptualisation comes from Glaessgen and Stargel:

> "A Digital Twin is an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding (…) twin. The Digital Twin is ultra-realistic (…)" (2012, p. 7).

Here, a Digital Twin is conceptualised as an extensive simulation that mirrors a physical entity in a realistic manner. Other examples of Digital Twin conceptualisations are as follows: a "comprehensive physical and functional description of a component, product or system" (Boschert & Rosen, 2016, p. 59), an "exact cyber copy

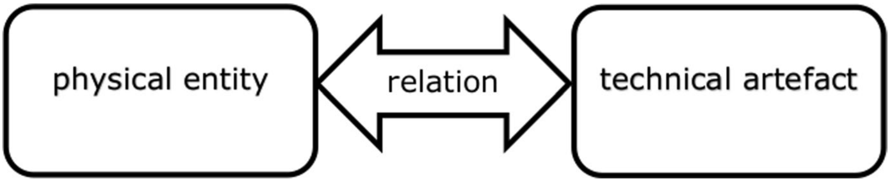

Fig. 1 Digital Twin: main elements

of a physical system" (Alam & El Saddik, 2017, p. 2051), a "virtual and computerised counterpart of a physical system" (Kritzinger et al., 2018, p. 1016), a "digital representation (attributes, behavior) of an entity" (Platenius-Mohr et al., 2020, p. 95), and a "digital equivalent of a real-life object" (Verdouw et al., 2021, p. 1). Despite the variety in terminology, the diverse conceptualisations do appear to have a similar structure that ties in to the name and consists of three main elements: a physical entity, a technical artefact, and a relation of representation between these two (Fig. 1).

Let us take a closer look at these three elements, starting with the physical entity. A Digital Twin has a one-to-one relation to a particular physical entity (Wright & Davidson, 2020). Examples of conceptualisations of the physical entity are "physical product", "physical artefact", "physical system", and "physical process" (see, e.g. Grieves & Vickers, 2017; Tao et al., 2018; López et al., 2020). The weight lies first and foremost on the physicality of the entity (Jones et al., 2020). In cases where the term "physical" is not employed, the used terminology is often still close in its meaning to physical, like "as-built vehicle or system" (Glaessgen & Stargel, 2012), "biological material" (de Lorenzo et al., 2021), and "body" (Shamanna et al., 2020). The potential scope and scale of the physical to which a Digital Twin relates is wide, ranging from singular entities on a cellular level (see, e.g. Shamanna et al., 2020) to a system or process on planetary level (e.g. the DestinE project). Concrete examples of physical entities are cells, aeroplanes, oceans, human bodies, tomato plants, factories, and planets. Moreover, the focus of the Digital Twin is on a particular individual physical entity. In case a Digital Twin is employed for a group of similar entities, the common approach seems to be to develop a prototype Digital Twin for the group, and then allocate an individualised Digital Twin to every specific singular entity (Grieves & Vickers, 2017).

The second main element is the technical artefact. Digital Twins are not defined by any particular technology (Liu et al., 2020). They are described as making use of a variety of technologies, components, and applications, like artificial intelligence, machine learning, big data analysis, internet, sensors, servers, etc. The Digital Twin descriptions change with the affordances offered by technological developments. For instance, over time, Digital Twins shifted from being initially descriptive representations of a physical entity to representations that are more manipulable, by, for example simulating the effect of external forces on the behaviour of an entity (Grieves & Vickers, 2017, p. 85). However, one common characteristic of the technical artefact is identifiable: the Digital Twin is digital. This means that it is constituted by digital data processing, which can be understood in a broad sense ranging from relatively simple data gathering and analysis to the use of artificial intelligence. Overall, Digital Twins seem to include a mixture of sensor data, historical data, various models, and simulations. Moreover, given the descriptions of Digital Twins, we understand this digital technology to include the necessary “border” technologies and components, like sensors and steering systems that bridge between the digital and the physical world. Because Digital Twins are not defined by a particular digital technology, the concept has a certain technical flexibility that allows it to also include future technological developments. Next to the digital nature of the artefact, the conceptualisations of the artefact also reflect a particular role attributed to it: the technical artefact is primarily described as a representation of the physical entity. Here, the third element comes into play: the Digital Twin conceptualisation assumes a representative relation between the technical artefact and the physical entity. This relation is conceptualised as one of an informative likeness in which the technical artefact is expected to offer all the information that can be derived from the physical entity. This is clearly expressed in the Digital Twin conceptualisation of Grieves and Vickers in their frequently cited article:

> “a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level. At its optimum, any information that could be obtained from inspecting a physical manufactured product can be obtained from its Digital Twin.” (Grieves & Vickers, 2017, p. 94).

The manner in which a Digital Twin represents a physical entity belongs to the family of modelling and simulation technologies: a Digital Twin is often conceptualised in terms of being a kind of model, simulation, or both (see, e.g. Rosen et al., 2015; Grieves & Vickers, 2017; Schleich et al., 2017). However, this raises the question why a separate concept is used. What differentiates a Digital Twin from other model and simulation technologies? Because there seems to be not one clear demarcation criterion (cf. Wright & Davidson, 2020), we identify a set of “family resemblances”, as Wittgenstein would call it, that are shared among the Digital Twin descriptions. A “regular” model or simulation may share one or more of these traits, but when all are present, it is likely that a Digital Twin is at play. For clarity purposes, we listed the characteristics that we discuss with examples of their conceptual framing in Table 1.

First, a widely recognised key characteristic of the relation between the technical artefact and the physical entity is that the artefact represents the physical entity in real-time, which is achieved by an active data flow from the physical entity to the Digital Twin (see, e.g. Tao et al., 2018; Barricelli et al., 2019; Liu et al., 2020; Verdouw et al., 2021). The representation of the entity offered by a Digital Twin is thus not static but dynamic. An example of this is a representation of a tomato plant that “grows” along with its physical twin so that it mirrors the current state of the physical plant.[2]

[2] The Digital Twin project Virtual Tomato crops, https://www.wur.nl/en/show/The-Digital-Twin-project-Virtual-Tomato-Crops.htm, last accessed 15–04-2021.

Table 1 Relational characteristics

Characteristic	Conceptualisation examples
Real-time	Real time, ultra-high synchronisation, current state, dynamic updating, monitoring, not a static representation, life-cycle information
High-fidelity	Ultra-high fidelity, reflection, comprehensive, reliable, exact, represents all functionalities, very realistic, mirror, combining information, fully describes, duplicates precise, accurate, information-rich
Predictive	Prediction, prognostics, probabilistic, aggregate future states, continuous forecasting
Prescriptive	Improvement, solve problems, optimisation, efficiency, reconfigure, diagnostics, health management, uncover issues, recommend changes, increase lifespan and success, performance assessment, failure alert, desired/undesired behaviour, anomaly detection
Feedback	Integration, interaction, bi-directional, entangled relation, fusion, control command, change, seamlessly integrated, activating self-healing mechanisms, mitigating damage or degradation, linked, interoperability, feedback loop, calibration, correct, decision-making, self-evolution

Second, the representation is conceptualised as "realistic", "very realistic", "ultra-realistic", "high-fidelity", "ultra-high fidelity", or "full". It is expected to provide information about the physical entity from multiple perspectives, like of a representation of the entity on a micro- as well as on a macro-level (see, e.g. Glaessgen & Stargel, 2012; Grieves & Vickers, 2017; Tao et al., 2018; Jones et al., 2020). While models are generally understood as an abstraction of reality, the strong focus on realism and comprehensiveness in the conceptualisations suggest that a Digital Twin aspires to move beyond being an abstraction and instead represent all functionalities of a concrete physical entity (see, e.g. Alam & El Saddik, 2017), and in some cases even suggest a kind of hyperrealism. Zhang and colleagues for instance state that "the characteristics of the virtual model can be more 'real' to show [the] physical entity" (Zhang et al., 2021a).

Third, Digital Twins are commonly ascribed predictive qualities (Barricelli et al., 2019; Liu et al., 2020; Verdouw et al., 2021). The representation is expected to reflect potential future states of the physical entity, like the entity's future behaviour, its degradation, and the effects of the environment on the entity (see, e.g. Grieves & Vickers, 2017; Schleich et al., 2017; López et al., 2020).

Fourth, many conceptualisations ascribe a certain prescriptive quality to the Digital Twin, although the exact form and weight thereof can differ per twin (Barricelli et al., 2019; Verdouw et al., 2021). This prescriptive character of the Digital Twin is reflected by the use of words like "optimise", "increase efficiency", "anomaly", "deviation", "undesired", and "correct". The Digital Twin is expected to signal deficiencies in the physical entity and/or to offer directions for optimisation. A Digital Twin thus not merely describes the physical entity it represents, but also prescribes how the physical entity ideally should function.

From this, a fifth and last characteristic follows that seems widely shared: there is some form of feedback from the Digital Twin to the physical entity, either directly by autonomous systems, indirectly by informed decision-making, or by a combination (see, e.g. Tao et al., 2018; Barricelli et al., 2019; Wan et al., 2019). For example, Zhang et al. write: "By leveraging means of data to simulate the behavior of physical entities in the real environment, the functions of physical entities can be optimized and expanded, through virtual and real interaction feedback, data fusion, decision making, and optimization" (Zhang et al., 2021a, p. 1).[3] In a similar vein, Alam and El Saddik attribute to a Digital Twin the ability to "send control commands to make necessary changes in the physical world" (Alam & El Saddik, 2017). Together with the real-time input, the feedback establishes a highly connective relation between the technical artefact and the physical entity. This is articulated in the conceptualisations by terms like "real-time sensory fusion" (Alam & El Saddik, 2017), "integrated" (Glaessgen & Stargel, 2012), "bi-directional" (Schleich et al., 2017, Van der Valk et al., 2020), "interaction and convergence" (Tao et al., 2018), and "interaction feedback" (Zhang et al., 2021a).

These five characteristics together typify a Digital Twin as an attempt to create digital representations that transcend being abstractions by minimising the temporal and spatial distance between the representation and the represented: by being real-time and connected to the physical entity by means of a bi-directional data flow, the representation is highly dynamic, and follows the physical entity, and intervenes in it. Unlike many models that reflect a theory and work "downward" to translate this into a reflection of a concrete phenomenon (see, e.g. Winsberg, 2019), the Digital Twin representation thus shows also a certain "upward" directionality where it receives input directly from the represented physical entity and is adjusted on the base of concrete phenomena and then, in turn, feeds back into the entity.

Simultaneously, our analysis so far shows an ambiguity in the conceptualisation of Digital Twins. On the one hand, Digital Twins claim to represent the physical entity but on the other hand, they are conceived as prescriptions that actively feed back into the physical entity. With prescription and feedback as characteristics of a Digital Twin, questions rise about the conceptualisation of a Digital Twin as a representation: if a Digital Twin is expected to actively intervene in a physical entity, is it really only a representation? We will delve into this in the next section. We will turn our attention to critically analysing the assumptions underpinning the Digital Twin conceptualisations in order to identify ambiguities and potential weaknesses.

3 Interrogating Digital Twin Conceptualisations

The conceptualisation of Digital Twins as high-fidelity or realistic representations suggests a certain secondary positioning of the Digital Twin to the physical entity: there is a dependence of the Digital Twin on the physical entity in order for the Digital Twin to be a re-presentation — the presence of the physical entity, again — of

[3] In some of the recent conceptualisations, autonomous systems are given a stronger defining role. Some authors argue that the ability to operate autonomously is a demarcating criteria that distinguishes Digital Twins form other types of digital modelling (see, e.g. Liu et al., 2020). However, because there is no consensus on this level yet and we also perceive an advancement of Digital Twins in policy development as a tool for non-automated informed decision-making, we employ a broader view that includes Digital Twin conceptualisations with non-automated forms of feedback.

this entity. A Digital Twin hereby is assumed to demonstrate a certain likeness to the original and is presented having a certain subservience (i.e. “fidelity”) to the physical entity. However, next to being conceptualised as a high-fidelity representation, Digital Twins are also ascribed more prescriptive functionalities, thereby suggesting a forming role towards the physical entity. The conceptualisations thereby exhibit a certain ambiguity in framing the Digital Twin as being merely descriptive (following) and being prescriptive (directing). This raises the question if a Digital Twin is accurately reflected by the manner in which it is conceptualised. In this section, we therefore question the dominant conceptualisation of a Digital Twin as a realistic representation of a physical entity and try to get a grip on its more elusive functioning. We do this in three steps: first, we challenge the ascribed realism and fidelity of the representation by demonstrating that a digital representation is necessarily something different than that which it represents and is therefore never a neutral representation. Instead, it is something extra to the physical entity, a “datafied surplus”. Next, we discuss how at the same time the digital representation substitutes the physical entity in the practices brought forth by a Digital Twin and the implications that may have for our engagement with these physical entities. After that, we critically reflect on the prescriptive functionality of Digital Twins and question its conceptualisation as only a representation. We argue that, instead, it is better understood as a steering technique.

3.1 A Datafied Surplus

The attribution of terms like “realistic”, “high-fidelity”, and “accurate” to a digital representation reflects a belief in an “objective quantification” offered by data collection and processing (Van Dijck, 2014, p. 198). However, despite framing the Digital Twin as a high-fidelity representation, many articles in fact research how such a representation should be constructed (see, e.g. Schleich et al., 2017, Zhang et al., 2021b). This reveals that creating a high-fidelity representation by means of digital modelling and data analytics is not evident, and rightly so. Research in the fields of science and technology studies and philosophy of technology has shown that technology is inherently not neutral. Marcuse for instance argued that technology establishes relations of power and domination between people and between humans and nature (Marcuse, 1976), while Ihde shows that technology affects the relation between humans and the world by co-shaping human goals, perception, and knowledge (Ihde, 1990). Additionally, scholars in semiotics and philosophy of science have been questioning the relation between representations and reality. Notable examples here are Peirce who explored the relation between a sign and the object it represents (Peirce, 1974), Hesse who explored the character of the analogy that models bring about (Hesse, 2017), and Barad who investigates the entanglement between matter and meaning (Barad, 2007). By being both a technical object and a representation, a digital representation embodies an intricate entanglement between materialisation and signification, which raises questions such as: what kind of thing is this representation? How does the representation represent? To what extent is the representation truthful? And what knowledge does it offer? These questions are not new, nor specific for Digital Twins, but are typical for models as well as for digitisation in general (see, e.g. Frigg & Hartmann, 2020). Asking these questions, however, does allow us to expose the ambiguity in the conceptualisation of a technical artefact as a realistic or high-fidelity representation.

3.1.1 Unrealistic Descriptive Ambitions

Let us start with the simple observation that a digital representation of an apple does not grow on a tree. Considering the origin of digital representations exposes some of the challenges for conceptualising a technical artefact as a realistic representation. A digital representation is a complex materialised and codified artefact which "substance" consist of several layers of matter and codification, ranging from humanly visible objects on a screen at the top layer, to programme files, to machine language, to binary code, to volts, and finally to silicon and copper as we move down the layers (Hui, 2013). The creation of such an artefact therefore necessarily requires agents to make choices on the level of software (e.g. the used compilers, interface, function libraries, algorithms, parameter settings), hardware (e.g. type and use of sensors, available processing power), its measuring system (e.g. weight, length), its form (e.g. numbers, colour values, text), and its boundaries (e.g. what is still part of that which is being measured) (Kitchin, 2014; Wan et al., 2019; Winsberg, 2019). Additionally, legal restrictions or demands, resource limitations, or institutional interests may influence agents in their choices. The choices and selections underlying the digital representation are shaped by and entangled with the agent's interpretative acts which are influenced by the goals with which the technology is employed (e.g. optimisation, improved sustainability, etc.), the institutions in which it is embedded (e.g. commercial enterprises versus research labs), the (potentially unconscious) assumptions of those involved, like the designers, producers, and consumers, as well as the material characteristics of the artefact (Gitelman 2013; Van Dijck, 2014; Kitchin, 2014). A digital representation is thus the result of a process based on human choices and interpretations, in combination with the material characteristics of the representing artefact, in this case machine encoding, decoding, and computation. This process takes shape against the backdrop of a certain knowledge paradigm in the form of mathematical functions and assumptions about relations. This paradigm precedes the representation and articulates its outline. However, the framing of the representation along the lines of "realistic" and "accurate" may easily obscure the role of human interpretation and selection herein, as well as the influence of technical affordances, and may lead us into thinking that this is indeed what the entity is.

What is more, the conceptualisations implicitly reveal the presence of a pivotal set of predispositions in Digital Twins. As a Digital Twin is expected to perform diagnostics and optimisations, it appeals to a certain norm of what the physical entity should be: one cannot correct or optimise anything without an idea of what is good. Somewhere in the Digital Twin, there is thus a normative frame that reflects the potential outlines of what people consider to be an ideal of the physical entity. For instance, if one wants to employ a Digital Twin to optimise corn production, one needs to have an idea of what "good" corn production is, i.e. is this more produce, better taste, more yellow, etc.? It seems unavoidable that this normative frame affects a Digital Twin's design with regard to the chosen parameters, what data to include, what algorithms to employ, and how to intervene in the physical entity. A representation that does not represent what people consider important for the physical entity (e.g. a representation of a corn plant that reflects the volume of sound produced by the growing plant over time, but not the amount of corn) is useless for diagnostics and optimisation purposes. As a result, a normative frame — possibly in a form cut-down to some parameters and required minimal elements — is materialised in the Digital Twin's design. The concrete shape given to the Digital Twin by its designers thus embodies certain valuative decisions and selections (Feenberg, 1996). These materialised norms precede the digital representation that is created within their framework: the digital representation is therefore necessarily construed within the perspective of a potential idealised view. Materialised but not explicitly articulated, this normative frame can easily escape our attention and call into life a phantasmal objectivity of the Digital Twin.

While the Digital Twin discourse frames the digital representation as being realistic or high-fidelity, the above shows that this is an unrealisable ambition: the concrete construction of a digital representation is a process that involves human selection and interpretation, machine encoding, decoding, and computation, and a transformation that transpires between these two: it is a process in which signification and materialisation are interwoven in a translation of a physical entity into a particular datafied form. The representation is thus necessarily distinct from the physical entity and presents a different perspective. For example, take a digital representation of a grapefruit tree that shows in numbers the impact of various environmental factors and their relative weight on its growth. These numbers are not part of the real tree, but are a human translation of a real process into a recognised format for understanding and analysing the world around us. By being different, the representation is something extra to that which it represents: it is a surplus to the original (Derrida, 2016). In the case of a Digital Twin, the representation presents a certain view on the physical entity, its future states, and it reflects an outline of what the physical entity ideally should be. This supplementary character is shaped by the purposes and interests of those that create the representation. The digital representation is thus not a neutral realistic reflection, but a particular materialised outline created by human agents that navigate through various choices, selections, and technical affordances.

3.1.2 Incomplete

By being different from and extra to the physical entity, the surplus is also inevitably incomplete in its representation: a representation does not and cannot represent all potential information about something else. Contrary to the Digital Twin discourse that conceptualises the representation as realistic or full, there is in practice thus unavoidably something lacking in these digital representations. This is especially the case for digital representations of living entities and systems, which are difficult to completely model (Pylianidis et al., 2021). The datafication of living things requires agents to quantify them in a set of variables, which in turn depends on what data is and can be produced. A crucial role here is played by the affordances of the used technology. For instance, collecting data about a pig on the level of concrete external input (amount of food, supplements, medication) and output (amount of growth, excretion) is generally easier than collecting data about the animal's psychological state and comfort. Consequently, a "quantified animal" is construed, which is likely to underexpose "[t]he animal's qualitative experiences and the individual qualitative differences between animals" (Bos et al., 2018, p. 88). While such a representation can facilitate the efficiency of meat production, it offers little help to improve the animal's well-being.

Additionally, the digital representation can be incomplete due to a lack of knowledge of human agents. While the technical Digital Twin discourse seems to start from the premise that the physical entity is transparent and fully accessible, which may very well be the case in product engineering, this may pose a bigger challenge in the case of life sciences and Earth system sciences. For example, imagine the use of a Digital Twin of a forest that aims to safeguard its preservation. Its success for preservation will depend on the representation's completeness: everything that is lacking in the parameters because it is unknown or not registered will not be part of the optimisation calculations and therefore not taken into account. Remaining terra incognita, like the biodiversity of soil (Andújar et al., 2017), challenge the creation of a complete representation. Meanwhile, the consequence of using an incomplete representation for forest ecosystem management can be severe: optimisation for known-species may inadvertently unbalance the ecosystem due to knowledge gaps and push unknown or unregistered species into dire conditions, and in the worst case scenario, extinction.

While the technical discourse tends to approach the digital representation as being complete, and this may indeed be the goal, it seems an unlikely reality. The almost inevitable blind spots or limited sidedness of digital representations can raise problems if they remain unacknowledged and the representations are treated as being complete.

3.1.3 Norm Reversal

We also see another issue emerging. The Digital Twin discourse presents the physical entity as the norm for the digital representation: the representation needs to follow the original to be real-time and high-fidelity. However, the necessary selection, translation, and incorporation of a normative frame in the Digital Twin show a contrasting image: a certain normative view on the physical entity precedes the creation of the representing artefact. The digital representation thereby carries within it the normative frame against which the physical entity is measured and thereby also serves as norm for the physical entity. In this role, the digital representation compensates for certain assumed deficiencies of the physical entity: the physical entity is approached as something that is opaque, degradable, unpredictable, and imperfect — lacunas that need to be filled by the Digital Twin. The result is that the digital representation becomes an essential supplement for the physical entity because its existence is necessary for the entity to become transparent, predictable, and the best possible version of itself. As such, the Digital Twin projects a view of what the physical entity "truly" is. In turn, the physical entity construes what a Digital Twin is: without physical entity, no Digital Twin. This raises the question what the epistemic origin is of the Digital Twin.

3.2 A Digital Substitute

Another area of ambiguity emerges if we consider the digital representation's role as "twin" for the purpose of monitoring, data analysis, prediction, and optimisation calculations. By representing the physical entity, the digital representation imbues the entity with a certain presence in a digital context where the physical entity itself is necessarily absent. The digital representation thereby not only forms a surplus to that which it represents, but at the same time also substitutes it (Derrida, 2016). In the monitoring, diagnostic, prognostic, and optimisation practices, the digital representation passes itself off as if it was the physical entity and is treated as such. It is thereby subject to a significant degree of reification: a technical artefact is treated as the reality of a physical entity. Meanwhile, the physical entity depends on its digital substitute: it is the representation on which decisions rest for managing the entity. While the technical discourse frames the digital representations in terms of being "realistic" and "complete", it is the difference between the physical entity and its digital counterpart that makes the representations valuable. If they were literally identical, a digital re-presentation would not make sense. An important difference between the physical entity and the substituting representation is the difference between physical and digital being. Being digital, the representation does not have a "material analogy" to the physical entity like a physical scale model can have (Hesse, 2017): "A computational fluid dynamics simulation, used to model and simulate the behaviour of flowing air, is neither windy nor wet in itself" (Floridi, 2013, p. 321). Thus, while the Digital Twin has a strong focus on the physical being of the entity, its substitution is explicitly non-physical in nature. The digital nature of the representation affords fast virtual experimentation with endless copies and information gathering that cannot or is difficult to achieve with the physical entity it substitutes. The effectiveness of Digital Twins therefore lies in their multiplicity of digital representations, which allows detailed monitoring, tinkering with ideal states, making predictions, and calculating the best course of action. In this regard, the digital substitute is not and cannot be a real substitute but different from the original it represents. However, despite its benefits, the fundamental difference between the substitute and the original also raises questions about the implications of this substitution.

3.2.1 Affecting Relations

As the digital representation substitutes the physical entity in certain contexts and practices, it is likely to affect the relations (1) between people and the physical entity, and (2) between diverse stakeholders. First, by substituting the physical entity in practices of assessment, monitoring, prediction, and experimentation, the digital representation affects the manner in which people understand and engage with and around the physical entity. Due to the affordances of digital data, the digital substitute enables people to monitor, diagnose, and predict aspects of the physical entity at any time and from anywhere. For example, plugged into the internet, a Digital Twin of a potato plant could in theory be accessed and managed over vast distances in space by everyone with an internet connection 24 h a day from the comfort of their living rooms. However, this interaction will always take place with the digital substitute, and not the real physical entity. The risk would be that the more a Digital Twin becomes the primary focus of agents, the more the agents' attention for the original physical entity may decline or be restricted in time (Pylianidis et al., 2021). Here, a role reversal may occur due to which the substitute becomes the main object of understanding and engagement for agents, while the original physical entity becomes functionally a supplement to the substitute. For example, imagine a dairy farmer who is able to fully monitor and control the milk production through a Digital Twin. The farmer only occasionally needs to visit the cows in order to confirm whether the real process indeed matches the digital substitute's diagnostics and predictions. In this setting, the relation between the farmer and the real cows is reduced to a confirmation check for the correct functioning of the digital substitute. With the substitute in a central role, the physical entity is placed into an indirect or more distanced relation to end-users and stakeholders. This may even result in the alienation of stakeholders and end-users from the original physical entity. A pivotal question therefore is how and to what extend the digital representation will substitute the physical entity in our practices and understanding.

Second, the digital substitute may change relations and power distribution between existing stakeholders and may give rise to new power relationships and stakeholders. For example, the use of a Digital Twin for the production of crops can establish a new dependency relationship between a less digital skilled farmer, the end-user, and those with the digital know-how and access to resources, like software and consultancy companies that sell the software licence and do maintenance. Furthermore, the normative frame materialised in Digital Twins may incorporate the norms of certain stakeholders, and not others — thereby giving one group a potentially significant but concealed advantage over others. Another key question is therefore how Digital Twins are shaped by and will affect in-world relations between stakeholders. Especially in case of the use of a new technology in the public realm or for public policy, it is pivotal to ask who benefits and who is empowered by this technology (Jacobs et al., 2020).

3.2.2 Shaping Potentiality

The digital substitute also has a significant impact on the potentiality of the physical entity: the information generated by the digital representation is expected to flow back to the physical entity (see "Section 2"). Information in the form of predictions, diagnostics, and optimisations shapes the potential directions into which the physical entity is steered as it shows which future states will likely follow under what conditions and which courses-of-action are the most likely to achieve certain goals (see, e.g. López et al., 2020). This view on the physical entity offered by the substitute can expand the horizon for what is thinkable and possible with regard to steering the physical entity. Here, we can imagine that with the help of artificial intelligence courses-of-action can be identified that human agents did not (yet) think of. Think, for example of the humanly unforeseen moves in a game made by an artificial intelligence, like AlphaGo made.[4] However, at the same time, following the substitute may come at a risk of closing off certain options: possible developments of the physical entity that are not reflected by the substitute fall off the radar. By co-shaping the concrete directions for intervention in the physical entity, the substitute is performative: it moulds the physical entity towards its own reflections. This performativity, however, may risk becoming a recursive cycle: with its real-time information input and feedback centred around a digital representation, the Digital Twin entails a continuous reproduction of a physical present into a digital representation and a continuous feedback of recalculations of this representation into the physical now. In such a feedback loop, the physical entity and digital substitute performatively grow closer towards each other.

This performative cycle raises the question whether and to what extent it will be possible for the physical entity and stakeholders to deviate from or open-up the courses-of-action proposed by the Digital Twin. Will the Digital Twin's recursive performativity give sufficient room for dynamic processes that tend to be considered valuable in real world developments, like innovation, creativity, spontaneity, and heterogeneity? Moreover, due to the substitute's impact on the evolvement of the physical entity, questions with regard to what the substitute represents of the physical entity and how become all the more pressing. Here, we again arrive back at square one: the choices made with regard to the creation of the digital representation. A Digital Twin thus places a considerable amount of decisive power over a physical entity in the hands of the people who shape the digital representation.

3.3 A Steering Technique

The important role attributed to feedback in the discourse suggests that some form of feedback is a pivotal part of a Digital Twin. With this active, bi-directional, and intervening character, a Digital Twin seems to do more than only fulfil the role of being a (particular digitised) representation. Instead, the representation seems to be an ingredient in a larger "recipe" — but a recipe for what?

With information and feedback as key elements for directing the physical entity towards optimal states, Digital Twin descriptions show a striking resemblance to cybernetic system theory. "Cybernetics" is based on the Greek verb *kubernaoo* (κυβερνάω), meaning "to steer", "guide", "govern", or "act as pilot". Cybernetic system theory is a theory that offers an understanding of the world based on information communication and control by means of feedback, also called "circular causality":

[4] https://www.theatlantic.com/technology/archive/2017/10/alphago-zero-the-ai-that-taught-itself-go/543450/. Last accessed 05–05-2021.

> "The circular flow of information allowed the system to compare its current state with a pre-set goal and take action to achieve that goal. The principles applied to living organisms, as well, such as the self-regulation of body temperature. The group's leaders referred to this process as *circular causality*" [emphasis original] (Kline, 2015, p. 39).

Digital Twin conceptualisations seem to share a foundational structure with cybernetics that revolves around directing a physical entity towards a desired state by means of information and feedback. In the context of cybernetics, Habermas draws our attention to an important distinction when he states: "It makes a difference, of course, whether we use a cybernetic frame of reference for analytic purposes or *organize* a given (…) system in accordance with this pattern" (Habermas, 1997, p. 106). In the case of a Digital Twin, the information and feedback structure serves as an organising — more aptly framed as "steering" — principle. Looking at a Digital Twin from this perspective and supported by the lack of a particular technology as identifying for Digital Twins, a Digital Twin may best be understood as a steering technique: based on information analysis, it steers a physical entity towards a particular goal. The information in this cyclic steering technique is provided by the digital representation. The representation is thereby a crucial part of the steering technique, but it is a part nevertheless: next to information about the current condition of the physical entity and its future states, also a goal, prescriptions, and action are required if the physical entity is to be steered. Understanding a Digital Twin from the larger perspective of a steering technique brings questions regarding its goals, how these are reached, and who decides what and when to steer, into sharper focus.

3.3.1 Techno-industrial Tendencies

Looking at a Digital Twin from the perspective of a steering method, we can see two main points of attention: (1) the goals towards which the Digital Twin is expected to steer, and (2) the question of who does the steering. Starting with the goals, in the technical discourse Digital Twins are said to be employed for the purposes of "optimisation", "efficiency", "better management and control", "diagnostics", "health management", to "increase lifespan and success", etcetera (see, e.g. Rosen et al., 2015; Schleich et al., 2017; Verdouw et al., 2021). With a focus on optimisation and efficiency, the goals overall seem to have a techno-industrial character. However, we can also imagine that by adjusting the design and feedback in different ways, Digital Twins can be tweaked towards goals that promote particular ethical agendas. Especially with quantifiable goals, we see potential here. For example, a Digital Twin could be used to find the best way to maximise the production of a tomato crop field without the use of pesticide. However, the question is if a Digital Twin can also steer towards more qualitative goals, like happiness of farm pigs. This raises a fundamental question about Digital Twins: do the goals follow from the characteristics of a Digital Twin or are these merely choices made by their designers in how to employ a Digital Twin? Given the important role of data science in Digital Twins, we can imagine that quantifiable goals are easier to aim for than more qualitative goals like happiness, empowerment, and overall well-being. However, is this inherent to the technique or are Digital Twins also fit to steer towards qualitative oriented goals?

A second key question is who is behind the steering wheel. This brings a dimension to the foreground that is not explicitly articulated in the dominant Digital Twin conceptualisations which describe a Digital Twin as a technical artefact that represents a physical entity: the human dimension. While the absence of the human agent in the Digital Twin conceptualisations may suggest a certain objectivity of the Digital Twin, we saw in "Section 3.1" that the Digital Twin is in fact build on an interplay of human choices, technological affordances, while being employed to serve humanly chosen goals. The designers, surrounding institutions, users, and stakeholders, are together behind the steering wheel by making decisions and shaping the technology and its context into the concrete form of the Digital Twin as steering technique that allows agents to exert a certain controlling power over a physical entity. This raises questions regarding power relations on a micro- as well as on a macro-level.

On a micro-level, the Digital Twin as a steering technique raises questions about who it is that influences this steering, to what extent, and what implications this has for other agents. The absence of the human agents in the Digital Twin conceptualisations focuses our attention on the instrumentality of the technique, while steering us away from its social implications: the power relations between the people involved as well as between them and non-users. Discussing these implications in detail here is beyond the scope of this article, but we will highlight some topics of concern related to the social implications of data processing which are identified and discussed in the literature. Access to resources is one of the key elements here: those who control the resources like the hardware, software, and data will be able to exert a significant amount of power over the Digital Twin and its use by others. With the central role of the digital representation in the functioning of the Digital Twin technique, questions with regard to data-ownership, transparency, explicability of the representation, data accuracy, bias, and trust will need to be answered in order to identify and assess the power relationships that Digital Twins bring about on a micro-level. For instance, whether data ownership is claimed and how this is organised, has a significant impact on the people that can use the data, as well as the goals for which they are used (see, e.g. Jones et al., 2020; Hummel et al., 2020). The material and social requirements of the resources needed for a Digital Twin may result in a significant corporate influence over the steering technique itself and/or in a data divide between data-rich and data-poor scientists and communities (see, e.g. Bezuidenhout et al., 2017). Furthermore, the processing of data into real-time representations and predictions raises questions with regard to the transparency, explicability, and fairness of algorithms that compile these representations, and to what extent people can, will, and should trust the software and those designing and distributing it (see, e.g. Wong, 2020; von Eschenbach, 2021; Tsamados et al., 2021). Moreover, when data relates to people, even if indirectly, the data can impact their privacy and establish power relationships based on a knowledge imbalance (see, e.g. Tavani, 2008; Galič et al., 2017). Last, the steering potential of Digital Twins and their expected application in policy context (e.g. the DestinE project that should help with the governance of climate change) raises questions about how Digital Twins will and should affect governance practices. These implications will require further research. Mapping the full scope of the diverse roles, power relationships, and corresponding impact of the people and parties that together form the "who" that is behind the steering wheel, is a study on its own and in all likelihood case-dependent.

On a macro-level, an implicit ideal of human control over the world seems to underlie the Digital Twin conceptualisations, and in particular control by means of data science and technology geared towards optimisation and efficiency. The control is thereby framed as external to the physical entity: it is a mix of human beings and machine calculations that decide on the goals, monitor, and steer. The physical entity is thereby made to serve a goal, instead of having a goal itself (Jonas, 1953). While this seems unproblematic in product engineering, this is different for research areas like the life sciences and Earth system sciences. The ambition of human control over the world by means of science and technology reflects a line of thinking that led to problems with natural resources and climate change in the first place (Blok, 2017; Lemmens et al., 2017; Zwier & Blok, 2017). Digital Twins may thus easily bring about certain power relationships and an extensive form of control under the guise of a techno-optimistic narrative about the Digital Twin as a high-fidelity representation. The question therefore is to what extent Digital Twins designed conform this line of thinking can offer a desirable solution to these problems. Here, we argue that it is precisely the lack of the human dimension in the Digital Twin conceptualisations that may be their biggest loss. Understanding Digital Twins explicitly as a potential steering technique for humans to employ, we can invite explorations of participatory governance and self-empowerment perspectives. A Digital Twin could promote participatory control of a physical entity by, for example including a wide group of stakeholders and allowing them to explore different future scenarios in order to find a balance between the interests involved. Employing Digital Twins to promote stakeholder or public participation requires spending attention to factors like transparency and accountability in the design and context of use (Jacobs et al., 2020). For this, Digital Twin research could draw on governance research in the context of smart cities (see, e.g. Jacobs et al., 2020; Wang, 2021). Especially transparency in the case of Digital Twins seems pivotal in order to be able to reveal and responsibly address their controlling mechanisms, as it can help to safeguard fairness and instal trust (von Eschenbach, 2021). Also, we can imagine a Digital Twin as a technique for self-steering by the physical entity, for example when a person uses a Digital Twin to monitor and manage their own medication use. A Digital Twin could thereby empower its physical twin instead of placing it under control of an external agent. Yet, the question remains if, and to what extent, the characteristics of a Digital Twin will allow such uses. The potentially strong governing role of Digital Twins therefore also raises the question how the digital itself in the case of a Digital Twin should be governed (Floridi, 2018).

Now that we have this critical concept of Digital Twins as a techno-industrial steering technique, we can question to what extent Digital Twins can offer support in addressing the core of issues like climate crisis and serve the development of a progressive Green Deal agenda as the European Union is proposing. To what extent are techno-industrial goals necessarily ingrained in Digital Twins: do the affordances of Digital Twins inherently promote or impede certain goals? And who does this technique empower to steer? Who benefits from the technique? The answers to these questions require a close inspection of the technique, its practices, its users, its designers, and its material characteristics, so that we can identify a Digital Twin's inherent limitations and its potential for gearing it towards realising different ideals. This further research is necessary to show possible future directions for Digital Twin development, as well as help to decide for which kind of problems and practices a Digital Twin is an advantageous tool, and for which it is suboptimal or unfit.

4 Conclusion

In the technical academic discourse, Digital Twins are conceptualised as virtual replicas of physical objects that reveal, predict, and optimise their physical counterpart. However, as we set out to critically question these conceptualisations, we found that the Digital Twin is not a twin. The denominator "twin" calls forth a simplified frame and suggests an equal relation between both "twins". As a metaphor, the notion "twin" transfers a relation of sameness (the digital representation has the same attributes as the physical entity) as well as a relation of equality (the digital representation relates to the physical entity as an equal) to the Digital Twin. As we have shown, it is precisely on these points that the ambiguity of the Digital Twin conceptualisations is the most critical: the digital representation is a translated surplus that is necessarily different from the physical entity, and by substituting the physical entity it takes in a dominant and steering position. When clearing up the conceptual clutter surrounding Digital Twins, an image arises of a steering technique that relies on a non-neutral and incomplete representation that is caught up with the physical entity in a recurring cycle of real-time updates and intervention in order to steer a physical entity towards certain prescribed goals. This process is underpinned by normative framing and instances of inclusion and exclusion on several levels. Moreover, the dominant concept seems embedded in a techno-industrial way of thinking that relies on the quantified approaches offered by data science. The conceptualisation of a Digital Twin in the technical academic discourse as a high-fidelity representation thus masks this intricate process of framing, selecting, shaping, and intervention that takes place against the backdrop of a certain knowledge paradigm and normative frame.

As we have seen, the implications of the concept's ambiguities and underlying assumptions are a reason for concern, especially in the context of life sciences and Earth system sciences. The non-neutral and incomplete representations can affect how we understand and engage with living entities and the world around us, while the steering technique may provide us with a new degree of control over this world. And while we maintained a focus in this article on the problems at a micro-level, namely, on the level of the technique itself, the problems also are tied to and spill over into the macro-level. The introduction and understanding of a new control technique likely affect governance, politics, relations between companies, institutions, demand for certain resources and know-how, access to knowledge, etc., which all require further exploration. Moreover, an extensive in-depth analysis of the human dimension of the technique is required: while absent

Table 2 Towards a critical concept of Digital Twins

Assumption	Critique	Research question
"Twin" presupposes a relation of equality between the Digital Twin and the physical entity	There is a hierarchical relation between the Digital Twin and the physical entity	What are the implications of the hierarchical relation between the Digital Twin and the physical entity?
Assumes realistic/high-fidelity representation by the technical artefact	The representation offered by the technical artefact is a non-neutral translation by human beings that reflects certain norms	How should we understand and deal with the non-neutrality of the representation in Digital Twins' design and use?
Presupposes complete transparency of the physical entity	Knowledge and information of the physical entity are never complete	How should we understand and deal with incompleteness in the design and use of Digital Twins?
The technical artefact represents	The technical artefact adds and substitutes	How should we understand and deal with the surplus and substitutive character of Digital Twins and the establishment of new power relationships and dependencies in Digital Twin design and use?
The Digital Twin provides feedback to the physical entity	A Digital Twin is a technique for agents to steer a physical entity	How should we understand and deal with the form of control realised by Digital Twins and account for factors like transparency and accountability in Digital Twin design and use?

in the dominant Digital Twin conceptualisations, the human being as designer, user, researcher, etc. plays a pivotal role in the creation and practices of Digital Twins. By suggesting a critical understanding of Digital Twins as a steering technique, we brought this dimension into the picture, but still more research is to be done on this point. Also, more research is needed to better understand ambiguities between, for example the applicability of data and validity of its use in Digital Twins, the exact relation between the physical entity and its representation in different types of Digital Twins, and between the description of the physical entity and the prescription of how it should be. We are thus only at the beginning of identifying all the issues revolving around Digital Twins. In Table 2, we listed an overview of the main issues we identified so far with the dominant conceptualisation. Advancing a critical concept of Digital Twins is important because if for instance policy makers seek to employ Digital Twins for the development of policies for improving sustainability or battling the climate crisis, a simplistic understanding of what a Digital Twin is and does can lead to wrong expectations, miscommunications between scientists, engineers, and policy makers, and in the worst case scenario, to wrong policy decisions.

Yet, despite the challenges, we also see great beneficial potential of Digital Twins for addressing issues on the level of sustainability, climate change, and harm-free experimentation. However, if we want Digital Twins to rise up to the challenges in a satisfactory manner, it is important to work with a critical concept of Digital Twins that understands it as datafied surplus, digital substitute, and steering technique. Such a critical understanding can help us pose questions about how to deal with the non-neutral, substitutive, and steering character of Digital Twins in their design and use. Moreover, a critical understanding can support the societal understanding and acceptance of Digital Twins, as well as offer a better view on their risks, benefits, and capacity to include of a wide set of societal norms and interests.

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