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Enhancing innovation via the digital twin

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Abstract

A growing number of firms are seeking to leverage emerging technologies, such as artificial intelligence (AI) and 3D printing, to enhance their innovation efforts. These seemingly distinct technologies are currently coalescing into an encompassing new technology called the digital twin. This technology allows innovative firms to create a digital replica of a physical entity that evolves over its life cycle. This article explores the implications of the digital twin for innovation theory and practice. First, we examine the connection between the digital twin and three related technologies (i.e., 3D printing, big data, and AI). Second, we create a typology of four categories of digital twins (i.e., monitoring, making, enhancing, and replicating) and illustrate their relevance for innovation management. Third, we offer a set of four case studies that exemplify this typology and illustrate how digital twins have been put into practice. Fourth, we craft a set of digital twin-related future research directions that encompasses a broad range of innovation-related topics, including service innovation, co-creation, and product design. We hope that our examination of the digital twin serves as a catalyst to help advance innovation thought and practice in this intriguing new domain.

KEYWORDS

3D printing, artificial intelligence, big data, digital twin, Industry 4.0

1 | INTRODUCTION

Industry 4.0 technologies such as artificial intelligence (AI) and 3D printing are currently disrupting our economy and transforming the manner in which firms engage in innovation management (e.g., Rindfleisch et al., 2020). To remain competitive in this new environment, firms are seeking to leverage these technologies to develop innovative new products and accelerate their speed of innovation (Davenport et al., 2020; Milan et al., 2020; Ojha et al., 2020). In this catalyst, we seek to advance both innovation thought and practice by examining how these innovation challenges may be surmounted via a digital twin (i.e., a digital replica of a physical entity that evolves over its life cycle) (Austin et al., 2020; Cooper, 2021; Grieves & Vickers, 2017; Parrott & Warshaw, 2017).

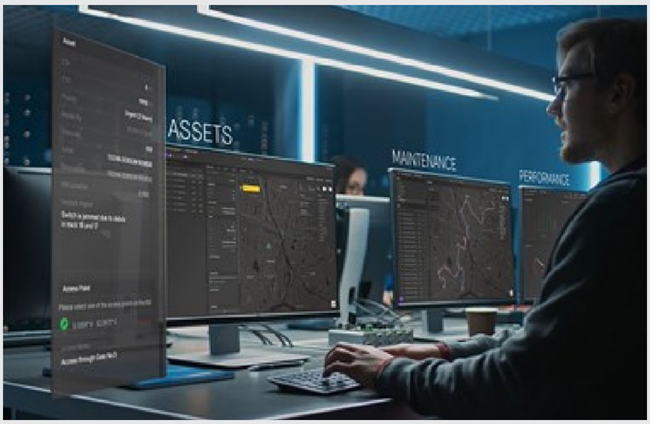
Although this technology is still in an early stage of development, digital twins are currently employed by a number of leading firms, including Dell, Microsoft, and Unilever (Handley, 2020; Smith, 2019) and are gaining interest from scholars across several disciplines, including engineering, medicine, and agriculture (Angin et al., 2020; Corral-Acero et al., 2020; Shao & Helu, 2020). In addition, digital twins have been applied in a wide variety of domains, including architecture, ecology, distribution, and manufacturing (Abrams, 2021; Burgos & Ivanov, 2021; Coors-Blankenship, 2020; Roaten, 2021). According to Microsoft CEO, Satya Nadella, the Digital Twin is "one of the biggest trends in technology" (Thornhill, 2020). As an example, he recently referenced a new digital railway initiative called WillowRail. As shown in Exhibit 1, this initiative seeks to transform railway operations by creating digital replicas of physical railroad tracks and deploying digital sensors that capture and transmit real-time usage data. This digital replica promises to dramatically enhance a rail operator's ability to predict and respond to potential problems before they occur, improve operational efficiency by minimizing downtime, and consequently, enhance the customer experience. We seek to contribute to this domain by examining the implications of the digital twin for innovation thought and practice. Since the digital twin is in a nascent stage of development, our approach is forward-looking in nature and seeks to provide a catalyst for future innovation management scholarship and practice.

As illustrated by the WillowRail example, the value proposition of a digital replica is quite broad. Specifically, we propose that digital twins have the potential to enhance multiple innovation-related functions, including upstream activities such as operations and supply chain innovation, as well as downstream activities such as innovating the customer experience. Innovation involves many different forms, including product innovation

Practitioner points

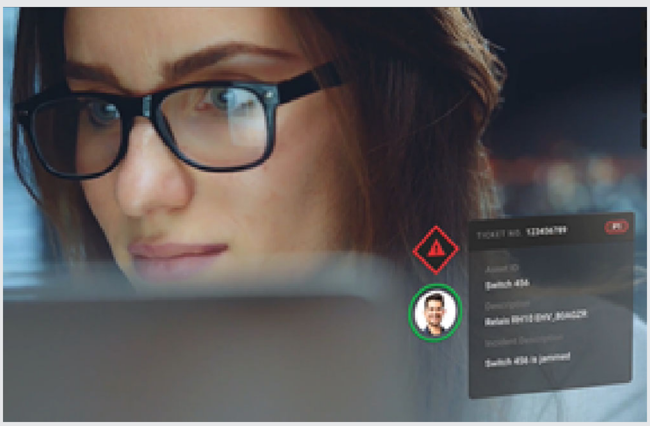
- The digital twin is a new emerging technology that allows firms to create a digital replica of a physical entity that evolves over its life cycle.
- The digital twin integrates a number of other Industry 4.0 technologies, including 3D printing, big data, and artificial intelligence.
- The digital twin allows firms to enhance their product and process innovation efforts in four distinct ways (monitoring, making, enhancing, and replicating).

EXHIBIT 1 WillowRail (railway operations Digital Twin)

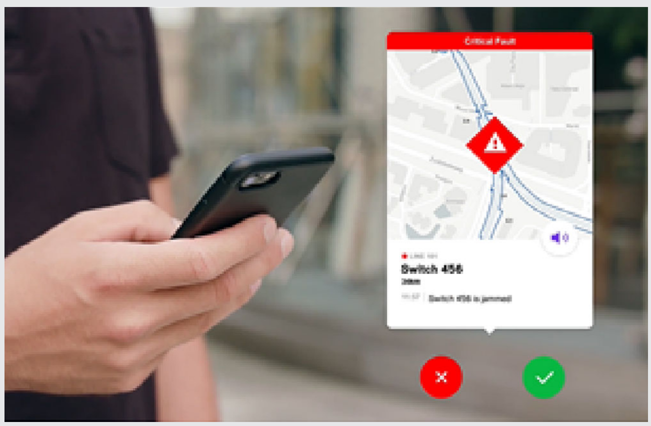


Overview: The digital twin allows WillowRail to obtain a digital replica of the real-time conditions of its railway operation.

Step 1: The digital twin enables railway operators to predict operational issues by detecting components (e.g., switch) that could malfunction before an actual breakdown.



Step 2: Details of the faulty component are sent to an operator, who opens a service ticket, and assigns a maintenance worker to the ticket.



Step 3: A maintenance worker receives information about the faulty part (e.g., Switch 456) on a mobile device and goes to the location to fix the issue to avoid an operational disruption.

Source: WillowRail (2020).

(innovating new products), as well as process innovation (improving the efficiency and effectiveness of a process) (Sawhney et al., 2006). Likewise, digital twins can be either product-oriented, by focusing on digitizing a physical product or service, or process-oriented, by focusing on digitizing various processes such as manufacturing or distribution. Thus, we examine both product-oriented and process-oriented digital twins and investigate their implications for both upstream and downstream innovation-related activities. These activities are relevant to innovation management because they represent a fundamental transformation of the manner in which new offerings are created, distributed, and/or consumed (Grieves & Vickers, 2017; Sawhney et al., 2006).

We begin our investigation of the innovation implications of digital twins by first providing an overview of this new technology and examining its connection to three key emerging technological trends: 3D printing, big data, and AI. We then propose a typology of four distinct categories of digital twins (i.e., monitoring, making, enhancing, replicating) and provide a set of case studies that illustrate each category. We then conclude by offering a set of research questions that will hopefully stimulate additional inquiry into this emerging and exciting new technology.

2 | OVERVIEW OF THE DIGITAL TWIN

Although digital twin applications have just begun to emerge, the concept of the digital twin is approximately 20 years old. The digital twin perspective regards the product lifecycle as consisting of two interconnected components (i.e., real space and virtual space). This concept was first introduced in 2002 by Michael Grieves, under the moniker, "Mirrored Spaces Model" and was subsequently identified as the "digital twin" in 2011 (Grieves, 2011; Grieves & Vickers, 2017). Like many advanced technologies, the digital twin has taken time to gain traction. In recent years, the digital twin has received a growing amount of interest from a wide array of organizations due to advances in related technologies such as 3D printing, big data, and AI, which have helped turn this concept into reality (Fuller et al., 2020; Lee et al., 2020). For example, Unilever recently partnered with Microsoft by utilizing Industry 4.0 technologies to craft a digital twin of its factory in Valinhos, Brazil. This initiative uses IoT sensors and sophisticated AI capabilities to analyze real-time big data as part of an effort to optimize its supply chain (Smith, 2019).

According to Tao and Qi (2019), digital twins are currently "revolutionizing industry" (p. 490) and recent reports indicate that approximately 30% of Global 2000 firms are experimenting with this technology as part of their innovation efforts (Ringman, 2019). As a result, the digital twin market is expected to expand to more than $35 billion by 2025 (MarketsandMarkets, 2019). As noted earlier, a digital twin is essentially a real-time synthesis of the digital and the physical. Thus, it consists of three main components, (1) a physical object, (2) a digital replica, and (3) a connection between the two (Alexopoulos et al., 2020). The connection between the physical and digital allows these two entities to share data in a reciprocal manner and leads to a process called "twinning," which refers to the synchronization of the physical with the digital (Cimino et al., 2019; Grieves & Vickers, 2017; Tao & Qi, 2019). This twinning process is facilitated by an array of technologies. Most notably, 3D printing allows a digital design to be materialized into a physical object, sensors placed on this object transmit large volumes of data to its digital replica, and this data is then analyzed with the help of AI (Austin et al., 2020; Qi et al., 2018).

Although much of the digital twin literature has focused on physical products (e.g., Haag & Anderl, 2018; Porter & Heppelmann, 2015), a digital twin could also include a digital replica of a physical process (e.g., Shao & Helu, 2020; Shao & Kibira, 2018). For instance, McLaren recently partnered with Deloitte and Dell to develop a digital twin that enhances the processes employed by both a race car as well as its driver. This initiative placed over 300 sensors on McLaren's race cars and also collected biometric data (such as heart rate) from its drivers to capture a trove of big data to help construct a digital twin (McLaren, 2020). This data was used to fine-tune the performance of not only its cars but also its drivers through the development of personalized training programs (Parrott & Warshaw, 2017; Verma, 2019).

A digital twin's unique ability to create a digital replica of a physical entity that can be continuously updated through its lifecycle has the potential to enhance a variety of upstream and downstream innovation-related activities. As an example of an upstream innovation application, GE Renewable Energy created a digital twin of its wind turbines (Rook, 2019). This digital twin enabled GE to enrich its process innovation by monitoring the real-time status of these turbines in operation, obtaining early alerts of performance deficiencies, and predicting potential breakdowns before they occur. As an example of a downstream innovation application, the government of Singapore recently created a digital replica of its entire city. The Singaporean government hopes to utilize this twin to enhance the well-being of its residents by simulating flash floods, detecting dead zones in its cellular network, and even identifying sheltered walking routes to provide protection from sudden rain (Dassault Systèmes, 2018). In this example, both static data (e.g., location of buildings) and dynamic data (e.g., sensor data to capture real-time flow of people) enabled the Singaporean government to create a digital twin that allows residents to view their city in entirely new ways (Dassault Systèmes, 2018).

3 | DIGITAL TWIN AND RELATED TECHNOLOGIES

As noted earlier, digital twins may be employed in conjunction with a variety of new technologies. In this section, we explore how digital twins connect to three of these technologies: 3D printing, big data, and AI. Our goal is to inform both innovation theory and practice by illustrating how digital twins can incorporate these various technologies to advance a firm's innovation activities. Each of these technologies play related but distinct roles in terms of twinning the digital with the physical. Specifically, 3D printing enables digital designs to be transformed into physical objects, big data enhances the integration of digital information with physical entities, and AI facilitates the operation of the digital twin. The role of each of these three technologies is depicted in Figure 1 and also incorporated in our future research directions.

3.1 | 3D printing (moving from digital designs to physical objects)

Due to its ability to straddle both the digital and physical, 3D printing is one of the most commonly employed technologies among firms seeking to implement a digital twin (Mukherjee & DebRoy, 2019). In essence, a 3D printer is "a manufacturing device that turns digital designs into physical objects by layering thin slices of a material in an additive process" (Rindfleisch et al., 2017, p. 684). As implied by this definition, 3D printing allows the digital to be transformed into the physical. For instance, Altair and MX3D collaborated to create a digital twin of a robotic arm by designing this arm via 3D modeling software and then transforming this digital design into physical form using a desktop 3D printer (Saunders, 2019).

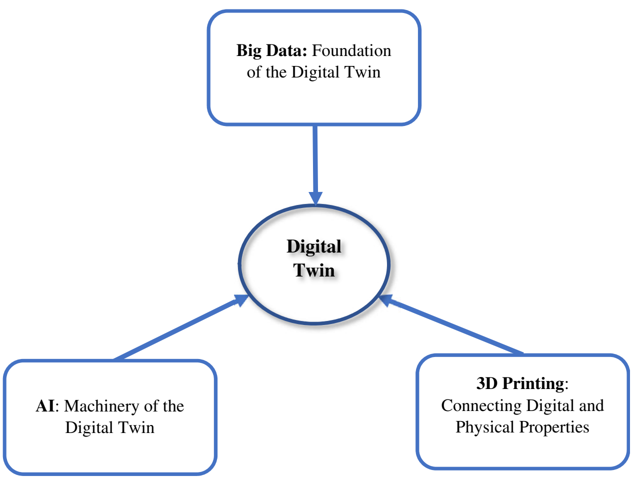


FIGURE 1 Digital twin enabling technologies

Likewise, Daimler partnered with EOS and Premium Aerotec to use 3D printing technology to create a digitally enhanced factory that produces aluminum parts for diesel engines (Jackson, 2019). By combining 3D printing and digital twin technologies, Daimler was able to reduce manufacturing costs and streamline its manufacturing processes (Jackson, 2019). In addition, Daimler plans to utilize 3D printing technology to digitize its inventory and develop an on-demand system to digitally manufacture replacement parts in place of a traditional physical inventory (Jackson, 2019). As illustrated by these examples, 3D printing technology facilitates both the design and creation of a digital twin. Moreover, because 3D printing enables firms to turn digital designs into physical objects, this technology facilitates the bi-directional flow of information between the digital and physical realms, which is an essential feature of most digital twins (Cimino et al., 2019).

The use of 3D printing also enables firms to extend the life cycle of existing products. For instance, Wichita State University, Dassault Systèmes, and the National Institute for Aviation Research are currently collaborating to create a digital twin of a B-1 bomber (a U.S. military aircraft manufactured over three decades ago) by 3D scanning its various components (Vinoski, 2021). This twinning process will enable customers to overcome part shortages by 3D printing spare parts on-demand. Without these technologies, many of these parts would be nearly impossible to obtain from existing suppliers. As seen by this example, the combination of 3D printing and digital twin technologies has the potential to not only revolutionize inventory management but also enhance sustainable innovation by allowing firms to repair (rather than replace) existing products (Juntunen et al., 2019). Consequently, these technologies can improve economic performance (by saving the costs of replacement) and environmental well-being (by prolonging a product life) (Juntunen et al., 2019).

3.2 | Big data (integrating digital information with physical products and processes)

Emerging new technologies, such as 3D printing, often generate large amounts of data. Due to its variety, volume, and velocity, this data-rich environment (i.e., big data) provides firms with a number of innovation opportunities and challenges (Bharadwaj & Noble, 2017; Rindfleisch et al., 2017). As noted by Davenport (2014), big data are "too big to fit on a single server, too unstructured to fit into a row-and-column database, or too continuously flowing to fit into a static warehouse" (Davenport, 2014, p. 1). This type of data (especially in the form of the Internet of Things (IoT)) is also essential to the development and deployment of a digital twin (Qi & Tao, 2018). For example, Chevron analyzes real-time data (e.g., temperature, oil flow) from sensors attached to various types of equipment (such as heat exchangers) to create digital twins of its oil refineries (Castellanos, 2018). These IoT-empowered digitized refineries enable Chevron to better predict when a piece of equipment needs to be cleaned and maintained to prevent potential operational breakdowns that could result in a significant loss of profits (Castellanos, 2018). Thus, digital twin technologies enable Chevron to achieve process innovation by redesigning a refinery process and improving its effectiveness and efficiency.

Similarly, the European analytics company Pygmalios is capturing big data by strategically placing sensors (e.g., 3D cameras on store ceilings) in physical stores. The data captured by these sensors are helping retailers build digital twins of their physical stores to enhance the customer experience (Marr, 2020). These digital twins have the potential to provide retailers with more detailed insights regarding the real-time status of their stores, optimize store operations, and enhance customer satisfaction (Tomlein, 2020). For example, Tesco employed Pygmalios' data collection tools to control the number of customers in its stores to meet recent Covid-19 restrictions; when a particular store reached maximum occupancy, a red signal was displayed at its entrance and a computer message asked customers to wait until a customer exited the store (Strategie, 2021). As seen from these examples, big data enhances a firm's ability to leverage a digital twin by optimizing the flow of information, improving operational efficiency, and converting disparate information into meaningful insights (Lee et al., 2020).

As detailed above, the integration of big data should enhance a firm's capacity to develop and deploy a digital twin. In addition, a digital twin may also enhance a firm's ability to successfully leverage big data. In essence, digital twins hold the promise of overcoming various obstacles that firms face when trying to utilize big data to enhance innovation such as the challenge of incomplete or dubious data (Bharadwaj & Noble, 2017; Erevelles et al., 2016). Recent research suggests that some of these obstacles are due to the difficulty of converging the digital aspects of big data with the physical aspects of new product development (Tao et al., 2018). A digital twin should enable firms to overcome this challenge by integrating the digital with the physical. As a result, a digital twin could enhance a firm's ability to better leverage data rich environments to enhance its innovation activities (Bharadwaj & Noble, 2017).

3.3 | Artificial intelligence (facilitating the operation of the digital twin)

According to Duan et al. (2019), AI is "the ability of a machine to learn from experience, adjust to new inputs and perform human-like tasks" (p. 63). In essence, AI is a technology that enables machines to autonomously engage in complex activities that have typically been performed by humans such as analyzing data, identifying patterns, and forming solutions (Huang & Rust, 2018; Shankar, 2018). In a digital twin application, AI can be employed to automate tasks to process both structured and unstructured data (Fan et al., 2021). For instance, Siemens utilizes AI (i.e., algorithms to model human organs) to process a wide range of both structured (e.g., lab results) and unstructured (e.g., medical scans, clinical opinions) patient data to create digital twins of human organs (Erol et al., 2020; Goled, 2021). In the future, these AI-powered digital organs could allow doctors to simulate different treatment options and obtain more accurate assessments of the costs and benefits of various surgical procedures (Fan et al., 2021; Goled, 2021).

While big data helps integrate the digital with the physical, AI leverages this data to facilitate the operation of the digital twin. Thus, these two technologies are closely connected (Davenport et al., 2020; Smith, 2020). For instance, GE recently acquired a number of AI firms (e.g., Bit Stew, Wise.io) to enhance its AI capabilities for processing the big data captured via its industrial devices (Reuters, 2016). This investment in AI has enabled GE to create over 1.2 million digital twins of its various products ranging from jet engines to windmills (GE, 2021). According to Colin Parris, the CTO of GE Digital, "in a digital twin, you have an AI system working with a physical thing. I see them as inseparable" (Essex, 2020). As illustrated in this quote, AI can facilitate the manner in which a digital twin operates by minimizing the need for human interaction (Lee et al., 2020; Longo et al., 2019). For example, Accenture offers firms an AI-powered digital twin solution (i.e., Intelligent Site Builder) to facilitate the installation of 5G networks by autonomously predicting which parts may be needed, identify which parts are out of stock, and even recommend alternative parts, if necessary (Tung et al., 2020). As a result, Accenture's human installers and suppliers can simply review and approve automated recommendations, and focus on higher-order tasks, such as

TABLE 1 Digital twin definitions

Source	Definition
Our definition[a]	"A digital replica of a physical entity that evolves over its life cycle"
Alam and Saddik (2017)	"An exact cyber copy of a physical system that truly represents all of its functionalities." (p. 2051)
Austin et al. (2020)	"A cyber (or digital) representation of a system that mirrors its implementation in the physical world through real-time monitoring and synchronization of data associated with events." (p. 5)
Boschert et al. (2018)	"A description of a component, product, system or process by a set of well-aligned, descriptive and executable models." (p. 209)
Cimino et al. (2019)	"Virtual copies of the system that are able to interact with the physical counterparts in a bi-directional way." (p. 1)
Grieves and Vickers (2017)	"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." (p. 94)
Hicks (2019)	"An appropriately synchronized body of useful information (structure, function, and behavior) of a physical entity in virtual space, with flows of information that enable convergence between the physical and virtual states."
Parrott and Warshaw (2017)	"An evolving digital profile of the historical and current behavior of a physical object or process that helps optimize business performance." (p. 3)
Porter and Heppelmann (2015)	"A 3-D virtual-reality replica of a physical product." (p. 100)
Sallaba et al. (2018)	"Virtual copies of physical objects or processes" and "consist of IT components for status updates, connectivity, defined data structures and user interfaces that visualize relevant data." (p. 4)
Schrage (2017)	"A virtual model of a process, product, or service." (p. 4)

[a]Our definition of the digital twin draws primarily from Austin et al. (2020), Grieves and Vickers (2017), and Parrott and Warshaw (2017).

communicating and engaging with project partners. Thus, as shown by this example, AI can facilitate the operation of a digital twin by minimizing human involvement and reducing project cost, which represents an example of business model innovation (Sjödin et al., 2020).

4 | TYPOLOGY AND CASE STUDIES

In this section, we provide a typology of four different categories of digital twins along with a set of illustrative case studies. This typology and set of cases should provides innovation researchers and practitioners with a deeper appreciation for variations of the digital twin in order to more precisely target their scholarly and managerial efforts.

4.1 | Typology overview

As shown in Table 1, the digital twin has been defined in various ways (Tao & Qi, 2019). For example, Grieves and Vickers (2017) define the digital twin as "a set of virtual information constructs that fully describes a potential or actual physical manufactured product" (p. 94), while Schrage (2017) define it as "a virtual model of a process, product, or service" (p. 4). In essence, some definitions focus on a virtual representation of a physical product (Grieves & Vickers, 2017; Porter & Heppelmann, 2015), while other definitions encompass processes and services (Parrott & Warshaw, 2017; Schrage, 2017). This definitional disparity reflects the substantial variance in terms of how digital twins have been applied across different industries. We account for this variance by categorizing digital twins across two dimensions: (1) Type of activity (i.e., upstream vs. downstream activities), and (2) Focus of application (i.e., process-focused vs. product-focused).

In terms of activity, downstream activities reflect efforts to enhance customer value and customer experience, while upstream activities reflect efforts to optimize manufacturing and supply chain activities (e.g., Dawar, 2013). In terms of application, a product-focused digital twin focuses on digitizing a physical product or service (e.g., an automobile), while a process-focused digital twin focuses on digitizing the process of developing, manufacturing, distributing, and consuming a product or service (e.g., the act of driving an automobile). These two dimensions reveal four distinct categories of digital twins: (1) Monitoring, (2) Making, (3) Enhancing, and (4) Replicating. Illustrative examples of each of these four categories are provided below (further details of each example are listed in the Appendix, Table A1). These examples (along with two additional examples of each category) are also depicted in Table 2. Currently, most digital twin applications appear to involve more upstream activities (monitoring and making) than downstream activities (enhancing and replicating) (e.g., Cotteleer et al., 2018; Rook, 2019).

TABLE 2 Digital twin typology

	Process-focused	Product-focused
Upstream activities	*Monitoring*: BMW created a digital twin to capture the status of parts, vehicles, and machinery, in order to optimize its factory's supply chain activities. Chevron used a digital twin to monitor critical components in its oil fields and refineries to minimize operation disruption. GE created a digital twin of its wind turbine to avoid the breakdown of critical components and improve operating performance.	*Making*: One Aviation collaborated with America Makes and Siemens to 3D print a digital twin of a bell crank for an aircraft. Electra Meccanica, a Canadian start-up partnered with Siemens to develop a digital twin to optimize the design and performance of a new compact three-wheeled electric vehicle (SOLO). MX3D, Altair, and ABB developed a 3D printed digital twin to optimize the manufacturing of a robotic arm by reducing its weight.
Downstream activities	*Enhancing*: A multifirm alliance among Intel, Bayer, Hewlett-Packard and Pfizer used CT and MRI data to produce a digital twin of a patient's heart to determine best treatment options. The Singaporean government created a digital twin of Singapore to improve well-being and safety of its citizens by simulating what would happen in case of an unexpected events, such as flash foods. McLaren used 300 sensors to create a digital twin of a racing car to provide drivers and crew with real-time status of its performance.	*Replicating*: ObEN created a digital twin of a popular TV host for China Central Television in order to facilitate the hedonic value of its contents through innovating the way to entertain the viewers. Digital Domain created "DigiDoug," a digital twin of Doug Roble that imitates his body and facial expression in order to offer a new tool of entertainment for filmmakers. The Metropolitan Museum of Art created digital twins of 400,000 pieces of its collection in order to make it freely available for non-commercial use.

Note: Italicized examples are described in our case studies.

4.2 | Monitoring: BMW

Monitoring refers to a firm's use of a digital twin to innovate various upstream processes, such as supply chain management. A good example of Monitoring is BMW's recent utilization of a digital twin to innovate its logistical processes (Garnsey, 2020). BMW constructed this digital twin by leveraging augmented reality (AR), 3D scanners, sensors, and high-resolution cameras (see Exhibit 2). Currently, BWM is partnering with Nvidia to deploy these digital twins in over 30 factories across the world (Caulfield, 2021). These twins allow BMW to construct digital images of various automobile parts and assemblies and also model its supply chain and logistical operations (Garnsey, 2020). This elaborate system of digital twins has helped BWM improve the efficiency of its factory assembly processes and achieved process innovation by digitally simulating the introduction of intelligent robots to improve the flow of its production line (Caulfield, 2021).

4.3 | Making: One aviation

Making refers to a firm's use of a digital twin to optimize the design and performance of a product through various upstream activities, such as product design and development. A good example of "Making" is One Aviation, a small aircraft manufacturer in New Mexico. This firm collaborated with Deloitte and Siemens to develop a digital twin to help design components of its jet aircraft (Cotteleer et al., 2018). In particular, it utilized a digital twin to optimize the design of a new bell crank (i.e., a lever used to control various types of motions such as opening a landing gear door). The use of a digital twin allowed One Aviation to digitally simulate potential points of operational failure such as unexpected jams and also digitally alter the bell crank's design prior to manufacturing (Gooch, 2017). In addition, this digital design also allowed One Aviation's physically dispersed new product development team to virtually design this part in a collaborative manner.

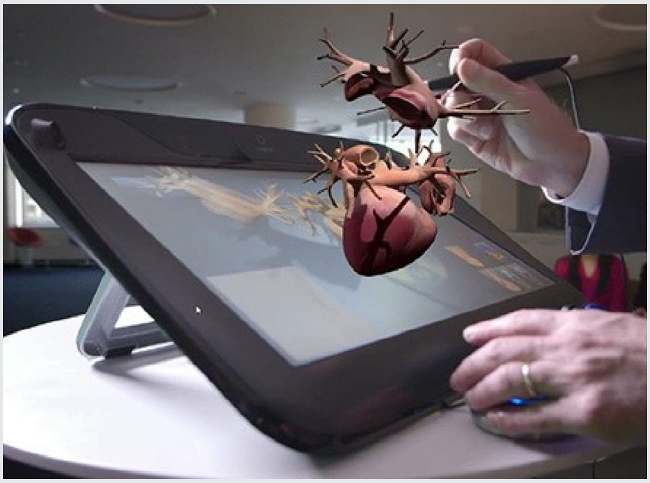
4.4 | Enhancing: Living heart project

Enhancing refers to a firm's use of a digital twin to manage various downstream processes, such as customer experience management. A good example of Enhancing is the Living Heart Project, a collaborative effort by several organizations across a wide range of institutions and industries, including medical researchers, software developers, pharmaceutical companies, and industry

EXHIBIT 2 Examples of digital twins

Digital twin of the supply chain activity in a factory (BMW) (Garnsey, 2020)

Digital twin of a bell crank for an aircraft (America Makes, Siemens PLM software, One Aviation) (Eckhoff, 2018)



Digital twin of a heart (Intel, Bayer, Hewlett-Packard Enterprise, Pfizer, and others) (Dassault Systèmes, 2014a)

A digital twin of TV hosts (China Central Television, ObEN) (Marr, 2019)

regulators (Shugalo, 2019; Sparrow, 2019). This project enables medical providers to create a digital twin of a patient's heart by collecting real-time data from IoT sensors and integrating digital images from CT and MRI scans. This new initiative will enable doctors to more easily assess a variety of health metrics (e.g., blood flow, cardiac defects) and, in some cases, replace more invasive procedures such as open-heart surgery (Shugalo, 2019). Moreover, this project could also stimulate medical innovation by allowing medical providers to simulate new, but unproven, medical procedures prior to implementing these treatments on a patient's body. In the words of Scott Berkey, the CEO of SIMULIA Dassault Systèmes, the Living Heart Project allows "whatever innovations researchers have to be tried digitally and not worry about the incorrect outcome" (Dassault Systèmes, 2014b).

4.5 | Replicating: ObEN

Replicating refers to a firm's use of a digital twin to optimize downstream customer experiences, such as developing a new way for customers to interact with a product or service. A good example of Replicating is ObEN, which recently created a digital twin of a famous Chinese television host (Marr, 2019). This initiative took place on China Central Television (CCT) during the 2019 Spring Festival Gala, where announcer Beining Sa co-hosted the event with his digital twin, nicknamed, "Xiao Sa" (Hu, 2019). This digital twin interacted with Beining Sa, and (through the help of machine learning) was also able to interact with CCT's audience by performing (i.e., singing and dancing) as an autonomous entity (Grace, 2019). Similarly, ObEN also created a digital twin of Adrian Cheng, the founder of K11 (a large Asian retailer) and used this twin as a virtual concierge to engage customers at a mall in Shanghai (ObEN, 2019). In the future, similar types of digital twins could be employed in online retail stores to enhance service innovation (e.g., Witell et al., 2016) by adding a human touch to the digital shopping experience (Marr, 2019).

5 | FUTURE RESEARCH DIRECTIONS

As noted earlier, digital twins are at an early stage of diffusion and deployment. Thus, scholarship on this emerging technology is still in its infancy. To date, prior research in this domain has been concentrated in disciplines such as engineering, medicine, and agriculture. As a result, the digital twin presents a wealth of research opportunities for innovation management scholars. In this section, we offer a set of research questions to help catalyze future research regarding the role of the digital twin in innovation management. In accord with our typology, these research questions are divided into two main categories: (1) Upstream activities and (2) Downstream activities, both of which are relevant to product innovation (e.g., manufactured goods innovation) and process innovations (e.g., services innovation).

5.1 | Upstream activities

As noted earlier, upstream activities refer to actions designed to optimize manufacturing and supply chain operations as part of a broader innovation value chain (Ganotakis & Love, 2012). Since a digital twin is "a single source of truth" (WillowRail, 2018), this technology could allow a firm to streamline real-time information and knowledge not only across multiple departments within an organization but also with external partners and suppliers. For instance, Willow (the developer of WillowRail) is currently developing a digital twin of the new SoFi Stadium in California (Willow, 2020). This digital twin will be built upon an array of big data captured across various parts of the stadium (e.g., gates, lighting, scoreboard) to optimize stadium operation and to innovate the visitor experience (Willow, 2020). As illustrated by this example, a digital twin can enhance both knowledge acquisition and utilization (Ordanini & Parasuraman, 2011). However, the specific impact of a digital twin upon these knowledge activities remains an empirical question. As a starting point, qualitative inquiry techniques such as ethnography and in-depth interviews could be especially helpful in understanding how knowledge-based innovation is affected by the adoption of a digital twin.

> **RQ1:** How does a digital twin impact a firm's innovation-related knowledge acquisition and utilization processes?

Due to rising competition, complexity, and costs, firms often engage in collaborative innovation activities such as new product alliances (Lau et al., 2010; Rindfleisch & Moorman, 2001). As documented by Rindfleisch and Moorman (2001), these alliances are often vertical in nature and typically involve information exchange between buyers and suppliers. Lau et al. (2010) propose that involving suppliers in the early stages of product design is increasingly crucial for successful product development. Given their cost and complexity, the development of a digital twin is also a collaborative endeavor. For example, a digital twin of a robotic arm allowed MX3D, a 3D metal printing company, and Altair, a software company, to collaborate and identify manufacturing challenges at an early stage of the product development process regarding the manufacturing and, thus, enhance its performance (Glabeke et al., 2020). Due to its ability to engage in continuous monitoring and real-time knowledge transmission, a digital twin has the potential to greatly facilitate new product-related information sharing between firms and their suppliers (Verganti et al., 2020). However, little is presently known about the effect of digital twins on collaborative innovation. In particular, future research could add value by examining the effect of digital twin technology upon information sharing between alliance partners. This type of question could be readily assessed via survey measures that assess the volume and nature of information sharing as well as the impact of this information sharing on new product outcomes.

> **RQ2:** How does the adoption of a digital twin impact information sharing between new product alliance partners?

In addition to providing a wealth of new information, the growth of big data is also altering the nature of resources required to engage in new forms of digital innovation (Erevelles et al., 2016; Niebel et al., 2019). For instance, in an effort to better control traffic with vehicular digital twins, the Los Angeles Department of Transportation (LADOT) launched a platform, called Mobility Data Specification, which asks ride-sharing operators like Uber to report the routes of their vehicle trips (Bliss, 2019). According to service dominant logic (SDL), one of the key features of this type of digitization is resource liquefication, which refers to the separation of information from a physical entity (Lusch et al., 2010). For example, by liquefying location data, platforms such as Uber are able to extract (and monetize) digital information from the physical activity of a vehicle in transit. In addition to resource liquefication, digital twins may also entail a high degree of resource mobilization (Goduscheit & Faullant, 2018). For instance, LADOT mobilizes both its internal resources (e.g., personnel to communicate with operators) and external resources (e.g., operators) to digitize vehicle traffic information. To date, the relation between resources and innovation has flown under the radar of digital twin scholars. Thus, future research can contribute to this domain by exploring the implications of the digital twin for resource utilization among organizations engaged in service innovation. For example, scholars could assess resource utilization by collecting and analyzing both structured and unstructured archival records (e.g., hiring and staffing reports, budget requests and email messages) before and after the implementation of a digital twin.

> **RQ3:** How does a digital twin affect and how it is affected by an organization's ability to utilize resources as part of their innovation activities?

5.2 | Downstream activities

As noted earlier, downstream activities refer to actions designed to enhance customer value and experience. Recent research by Atasoy and Morewedge (2018) suggests that customers may derive more value from physical goods than from digital ones. While this research is intriguing, it suggests that the physical and the digital are two distinct entities and that customers have to choose between one or the other. However, the emergence of the digital twin implies that customers may no longer be forced into this dichotomy and may have access to offerings that are simultaneously both digital and physical in nature (Grieves & Vickers, 2017). For example, Tesla's physical automobiles display a virtual image of the driver's vehicle and depicts its travel pattern in real time. Thus, Tesla customers drive a physical vehicle but can also track it digitally. Similarly, ObEN's digital twins of actors and actresses allow fans to experience both their digital and physical presence simultaneously. As new technologies such as 3D printing, big data and AI advance over time, it is likely that a variety of other customer-facing products will also become digitized. If so, firms will need to understand which types of products (e.g., utilitarian vs. hedonic products) customers prefer to experience as a digital twin instead of a separate digital or physical entity. Thus, the impact of this twinning activity upon preference for a particular product form is an intriguing question. To understand customer preferences for a digital product, a physical product, or a combination of these two forms (i.e., digital twin), scholars could either conduct experiments or extract insights from big data.

> **RQ4:** Under which conditions would a customer prefer: a physical product, a digital product, or a combined physical and digital product (i.e., digital twin)?

A considerable body of research suggests that customer preference is strongly influenced by a product's design (e.g., Patrick et al., 2019). For example, Moon et al. (2013) outline the importance of understanding the association between product innovation and product design and conceptualize design innovation as "new or substantially improved product design and product features that are created to satisfy customer needs" (p. 33). Based on empirical studies in both Korea and the United States, Moon et al. (2013) found that firms can enhance design innovation by creating not only technologically advanced products but also aesthetically pleasing products. Digital twin enabling technologies such as 3D printing, big data, and AI should allow firms to enhance product design. In particular, these technologies improve a firm's ability to capture customer preferences, simulate various design options, and rapidly prototype and manufacture new offerings that are both technologically innovative and aesthetically pleasing (Cantamessa et al., 2020; Eisenman, 2013). Thus, future research should seek to investigate the individual and collective impact of 3D printing, big data and AI upon product design. For example, scholars interested in this topic could craft experiments that compare customer response to traditionally designed products versus products created via digital twin-enabling technologies.

> **RQ5:** To what degree does a digital twin enhance product design (both technically and aesthetically)?

A growing number of companies are altering their business model to focus less of what they offer and more on the outcomes of their offerings (i.e., outcome-based services) (Sjödin et al., 2020). For instance, health care providers are increasingly shifting their focus from selling medical services to selling the outcomes of these services (e.g., the degree of improvement in a patient's health). Because customer-related outcomes may quickly change, the ability to regularly monitor these outcomes is critical to the success of this approach (Tinker, 2018). For instance, digital twin researchers are currently developing a wearable IoT-enabled ultrasound scanner that could be woven into clothing (such as a vest) in order to continuously scan a patient's heart (Economist, 2020). This type of wearable device could allow medical service providers to form a digital twin of a patient's heart and enhance service provision via increased diagnostic data and real-time communication. Future research could contribute knowledge of these types of outcome-based innovations by examining the degree to which digital twins help enhance the design and delivery of these types of services. For example, innovation scholars could equip customers with a digital twin of a critical activity and assess the impact of this twin upon their experience via a longitudinal survey approach.

> **RQ6:** To what degree does a digital twin enhance the customer experience in terms of outcome-based services?

6 | CONCLUSION

This catalyst explores scholarly and managerial implications of the digital twin in relation to innovation management. This exciting new technology has the potential to revolutionize both upstream and downstream innovation activities by twinning the physical with the digital (Maddikunta et al., 2021). Moreover, the digital twin intersects with a number of Industry 4.0 technologies, including 3D printing, big data, and AI. Thus, the processes and products developed through a digital twin have relevance for scholars and practitioners interested in these adjacent technologies. At present, digital twin technology is still in an early stage of development and somewhat disconnected from a firm's broader innovation strategy. Our investigation is forward looking in nature and provides a catalyst for future innovation management research and practice. First, we examine the connection between the digital twin and three related technologies (i.e., 3D printing, big data, and AI). Second, we create a typology of four different digital twin categories (i.e., monitoring, making, enhancing and replicating), and illustrate their relevance for innovation management. Third, we offer a set of case studies that exemplify this typology and illustrate how the digital twin has been put into practice. Fourth, we craft a set of future research directions in this domain that encompasses a broad range of innovation-related topics, including service innovation, co-creation, and product design. Looking forward, the rise of the digital twin suggests that the physical and the digital may be more closely related than commonly thought and that these two states should be viewed in combination rather than in isolation. Thus, we believe that the digital twin will be a critical component of the next stage of our unfolding digital revolution and that this emerging technology is worthy of greater attention from innovation scholars and managers.

ETHICS STATEMENT

The authors have read and agreed to the Committee on Publication Ethics (COPE) international standards for authors.

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APPENDIX A

TABLE A1 Additional case study details

	Process-focused	Product-focused
Upstream activities	*Monitoring: BMW*[a] BMW has also employed its investments in digital twin technology to enhance its manufacturing operations in its joint-venture (with Brilliance Automotive) factory in Dadong, China. This technology has improved the efficiency of manufacturing its 5 Series automobile by allowing BMW to use the vehicle identification number (VIN) to digitally track the production of each automobile through each step of the manufacturing process. As part of this tracking process, BWM employs optical lasers to scan the body of each of its 5 series models at a rate of 20,000 points per second. This scanning process is able to easily detect and correct manufacturing defects such as a adjusting a bolt that may have been tightened improperly. As a result of these digital twinning efforts, BMW has been able to automate 95% of its manufacturing operations in this particular factory, while reducing defects and enhancing product quality (BMW Brilliance Automotive, 2017).	*Making: One Aviation*[b] After digitally designing this bell crank, One Aviation's new product development team employed 3D printing technology (i.e., selective laser melting) to both prototype and manufacture this part (Cotteleer et al., 2018). In addition to physically printing this bell crank, One Aviation also used 3D scanning technology to digitally inspect and optimize its design prior to final manufacturing. The use of 3D scanning allowed the team to inspect over 1600 fine-grained layers to detect any possible discrepancies between the digital image and the physical part. In essence, the use of a digital twin allowed One Aviation to seamlessly iterate between the digital and the physical to optimize the design of this new component, reduce the risk of manufacturing defects, and optimize its performance before the plane leaves the ground.
Downstream activities	*Enhancing: Living Heart Project*[c] As part of this initiative, Dassault Systèmes is currently working with the US Food and Drug Administration to conduct digitally enabled clinical trials (called in silico clinical trial) of new cardiovascular devices (Sparrow, 2019). Due to its capability to simulate the functionality of these new devices, a digital twin allows device manufacturers, such as Novo Nordisk (a client of Dassault Systèmes), to rely less on physical testing on animals and human compared to traditional clinical trials. In a way, the digital twin enables these device manufacturers to test their new devices in a more sustainable and safer way, offer creative solutions to diseases, and implement social innovation (Lee et al., 2019). This replacement of the physical with the digital should improve the efficiency of clinical trials, make novel medical devices available to patients in a timelier manner, and thus, accelerate the speed of innovation. Dassault Systèmes, along with other partners, is currently applying digital twin technology to another human organ, the brain, in an initiative called the Living Brain Project (Levine, 2020). This new initiative is still in an exploratory stage but is expected to help physicians better understand brain injuries and help slow the progression of neurological diseases (Ribbink, 2020).	*Replicating: ObEN*[d] ObEN is currently creating digital twins of a variety of individuals (Marr, 2019). For instance, ObEN recently collaborated with Yoshimoto Kogyou, a major entertainment conglomerate in Japan to create digital twins of several actors and actresses (Cision, 2020). These types of digital twins provide hedonic value by offering viewers with new ways to virtually interact with their favorite actors and actresses. In contrast, ObEN is also working with a variety of medical professionals to create digital twins of doctors and nurses to provide utilitarian value by offering virtual consultation to patients.

[a]For more details of this case, see https://blogs.nvidia.com/blog/2021/04/13/nvidia-bmw-factory-future/.
[b]For more detail of this case, see https://sloanreview.mit.edu/video/following-the-digital-thread-the-digital-thread-takes-flight/.
[c]For more details of this case, see https://www.plasticstoday.com/medical/living-heart-project-beats-five-more-years-dassault-fda-renew-partnership.
[d]For more details of this case, see https://www.forbes.com/sites/bernardmarr/2019/01/29/the-worlds-most-watched-tv-show-will-be-hosted-by-artificial-intelligences/?sh=3c1c3aa468de.