HCI and Digital Twins – A Critical Look

A Literature Review

Fanny Vainionpää
fanny.vainionpaa@oulu.fi
University of Oulu
Oulu, Finland

Marianne Kinnula
marianne.kinnula@oulu.fi
University of Oulu
Oulu, Finland

Atte Kinnula
atte.kinnula@vtt.fi
VTT Technical Research Centre of Finland
Oulu, Finland

Kari Kuutti
kari.kuutti@oulu.fi
University of Oulu
Oulu, Finland

Simo Hosio
simo.hosio@oulu.fi
University of Oulu
Oulu, Finland

ABSTRACT

Digital twins (DTs) are one form of datafication. They are virtual reflections of physical world entities, of objects and phenomena, and are rapidly becoming an asset for innovation. There is a growing body of literature on DTs in various technology-related fields. A critical thread has emerged within this body, warning on the danger to forget that the digital part is always only a partial representation of real life, and that this partiality is always selective and biased for a specific purpose. It may thus serve some group of stakeholders better than others. We contribute with a literature review on the current understanding and use of the DT concept in the field of HCI. Our results consolidate the current understanding of DTs' potential in HCI and note the omission of the critical perspective within the reviewed literature. The paper opens discussion of what HCI can bring to DT development and use.

CCS CONCEPTS

• **Human-centered computing → HCI theory, concepts and models**; • **Computing methodologies → Artificial intelligence**.

KEYWORDS

Digital twin, Digital shadow, Digital model, Data, Datafication, Artificial intelligence, Machine learning, Intelligent technologies

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1 INTRODUCTION

The United Nations Agenda for Sustainable Development urges everybody to consider how their actions could advance "peace and prosperity for people and the planet, now and into the future"[1]. For example, Goal 10 [2], reducing inequality within and among countries, is very clearly within Human-Computer Interaction (HCI) agenda, as reducing inequality through hearing the voice of those who are somehow affected by new technologies is at the heart of HCI. However, listening is becoming all the time more complex with the intelligent technologies that are created to make our world more efficient and convenient, as their effect can be subtle and unnoticed, and it is not always clear who actually are affected by the technologies and how. One such technology are the so-called Digital Twins (DT) [27]. A DT is based on data, mirroring the physical world to digital form, and is envisioned to become an important part of the digital world [89] as the higher network capacity allows for example for collection of more sensor data in real-time.

DTs have become common in industry along with digitalization of machinery and production systems [21]. They are used in manufacturing to control factory processes [28] and in aviation for damage prediction [45]. Digital prototypes of products that have not yet been built, to trial out their properties and functions through simulation, have also been called DTs [10]. Although the DT concept was initially developed for manufacturing, the concept has since been extended to urban development and DTs of cities [16, 54], and even living entities, as in human-robot collaboration [44, 58], as well as with the intent to gain continuous feedback that can be used to improve quality of life [21]. In smart farming, DTs have been suggested to increase productivity and sustainability in agriculture where many farm operations can be monitored, controlled, and coordinated remotely (see e.g. [85]). Human DTs have also been proposed for various purposes from fitness management [6] to data- and model-driven healthcare [11] for monitoring stress levels [66] or heart condition [47]. When relaying (sensor) information of a real-world entity to the digital counterpart the DTs essentially 'speak' on behalf of those that do not have a voice: machines, soil, plants, human organs – or even intangible things such as processes. Armed with such information, users, operators, or in some cases automated systems can then take action to influence the real-world counterpart, forming a closed (feedback) loop system. The feedback loop, in turn, allows us to 'speak' to these

[1] https://sdgs.un.org/goals
[2] https://sdgs.un.org/goals/goal10

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entities, thus establishing a dialogue between us and the world, in a way that has not been possible before. However, one should remain conscious of the fact that even though DTs are designed for high-fidelity [41], it is impossible for them to be full copies of the real-world and consequently there is a possibility they miss a voice that should be included.

Inspired by the increased interest in data-driven perspectives in HCI field (e.g. [25, 76]) as well as Participatory Design (PD) researchers suggesting the new data-driven technologies as an important arena for PD [55] where PD practices for understanding and reconfiguring socio-technical systems might help in making better use of data [29], we wanted to examine in this paper the current understanding and use of the DT concept in HCI and design research. We present the findings from our literature review, asking as our research questions: *How has the DT concept been used in the HCI field so far? How could HCI conceptually address design challenges arising from the characteristics of DT?* Our general aim is to understand how to develop intelligent technologies – particularly DTs – that utilise machine learning and artificial intelligence (with the common denominator of data collection, curation, and modeling) in such a way that they support and advance inclusion and socially just practices, rather than create exclusion, and help us have a dialogue with also those who don't have a voice – be it animals, soil, or user groups such as disabled people, children, or elderly people. We link our work with the HCI tradition interested in critical, context- and practice-oriented approaches, and want to bring politics of design also to the discussion on DTs.

In the next section, we discuss the DT concept further, as a background for the literature review. Then, we describe our literature review methodology, and the findings of our narrative literature review that focused on HCI and design literature. Then, we discuss our findings, proposing a conceptual approach to DT for HCI based on technical characteristics of DTs, and finally conclude the paper.

2 THE DIGITAL TWIN CONCEPT

Even though the DT concept was presented already in 2002 [27] discussions around it started to appear more frequently in 2017 [32]. Now, the DT concept is listed in the *Accenture Technology Vision Report* as one of the top five strategic technology trends for 2021 [1]. Despite the wide use of DTs it seems that a precise definition is not set in stone [41] and various understandings exist for what the concept of DT refers to [39]. It has even been pointed out that it can be more difficult to say what is not a DT than what is a DT [63]. A shared understanding is that DTs are virtual representations of physical assets, made by using the data of the physical assets for the purposes of monitoring, controlling, decision making, optimization and even real-time prediction regarding those physical assets [63], i.e., they are based on data and they are data-driven. This means that the issue of data quality, completeness, and representativeness – and in the case of AI-powered DTs, the question of bias [69] – are central for the quality of DTs. A review of the literature found that the use of the term is wide, but the DT is commonly considered as a mirror of the physical twin, the DT can simulate the physical twin's behaviour virtually, the DT responds to the physical twin real-time, and changes in the DT or the physical twin change the other twin as well, i.e., they have a dynamic relationship [41]. In the same vein, DTs have also been described as computer-based models that simulate, emulate, mirror, or twin physical entities, including objects, processes, humans, or their features through continuous communication between the entity and its DT, and often the environment [5]. DTs can be seen as a way to accomplish convergence of the physical and virtual spaces and to enable smart operations [79]. The authors discuss a concept of a DT shop-floor with four key elements: the physical and virtual shop-floor, its service system, and the DT data.

The DT term is also sometimes used synonymously with a Digital Model or a Digital Shadow [39]. According to Kritzinger et al. [39], a Digital Model, Digital Shadow, and Digital Twin are different 'levels' of the concept, where a Digital Model is a digital representation of an existing or imagined physical object. While data can be used in aDigital Model, there is no automated data exchange. In a Digital Shadow there is an automated, one-way data flow from the physical object to the digital. Finally, when the data flows both ways between the physical entity and the digital representation, it is considered a DT. Then, the digital may be used to control or influence the physical. [39].

Central to understanding DTs is that they are always created for a purpose, i.e., a DT creates value based on data for a given stakeholder, and that they are only variable-based descriptions of physical objects, not full mirrors of those objects. The variables the DT uses as a basis of its analysis need to be chosen so that they are relevant ones from the DT functioning point of view. Thus, variable selection requires deep understanding of the physical world phenomenon, how it works, and how it can be controlled and managed. DTs are also always twins of single instances, i.e., with a couple of similar machines in a factory, there is a separate DT for each physical machine.

The value of DTs has been identified in the possibilities of remote monitoring and control, efficiency, safety, predictive maintenance and scheduling, scenario and risk assessment, synergy within and between teams and collaborations, decision support, personalization of products and services, documentation and communication [63]. In smart manufacturing [62], DTs enable assessment of products, processes, and servicing decisions and through that affect the competitiveness of manufacturing companies [67]. Methods of using data and DTs have been suggested for developing product design, manufacturing, and service towards better efficiency and sustainability [78]. When it comes to smart cities, data on infrastructure services has been envisioned to support decision making and management with DTs of the cities [51]. Similarly, a prototype of an urban DT of a town with 30 000 inhabitants was discussed from the viewpoint of potential solutions for public decision-making through democratization of urban data. In this, the DT included information about the environment, the street network, urban mobility simulation, wind flow simulation, and geographic information [15]. Such empowerment and inclusion perspective seems to be a clear direction for sustainable development of smart cities, as well as urban and regional areas [2].

There are also concerns related to the various DT applications: their accuracy and reliability, obstruction of normal living, security measures related to privacy, their ability to detect failure, how different cultures are accommodated, and legal issues related to responsibility and liability [21]. Challenges have also been identified in keeping a two-way connection between the physical and virtual for real-time interaction, uncertainty of physical elements, mirroring entities with high fidelity, identifying inconsistencies between models and entities, how to realize the seamless integration of the two sides, how to integrate and converge the increasing data, security, and the balance between costs and interests of DTs [79].

Because making computer models of real-life phenomena is one of the oldest uses of computers, the ideas related to the DT concept are not particularly novel, but continuation and combination of work done in older traditions, two of which can be highlighted here. First is the process control, where computers have been used since 1950s. A computer-controlled chemical process or a ship under autopilot are quite similar to the basic idea of a DT: there is a computer model corresponding a real-life process (a chemical process or a ship under way), the relevant aspects of the real-life situation are constantly monitored by sensors, and necessary corrections calculated based on the model fed back to real life by actuators. Another obvious ancestor to DTs is using computers in designing new artifacts: computer-aided design and in particular its further development: virtual prototyping. Virtual prototypes extend CAD models in that their various functionalities are also modelled and integrated to the digital models of the physical products, so that they can not only be seen, but also experimented with in a virtual environment. Virtual prototypes emerged as a concept in 1990s, and the United States Department of Defense published already 1994 a document named "*Virtual Prototyping: Concept to Production*" [23]. A decade later a literature review commented: "*Virtual prototyping techniques are being extensively used in industry worldwide*" [14]. Because of the product design orientation, information flow in virtual prototyping was initially rather one-directional: from a digital model towards a novel product. Recently, with a connection to product lifecycle maintenance (PLM) also later phases, such as use, maintenance, and omission have been recognized as areas where virtual prototypes could potentially be useful [80]. For this purpose, feeding information from real-life back to the model is needed, and thus it also comes close to the idea of the DT concept. The main novelty of DTs seems to be that technological progress has made both networking and computational power so ubiquitous, that potential application areas have expanded greatly both in scale and in scope, also beyond technical systems such as modeling for instance human health.

Given the popularity of DT concept, it is natural that there exists already a number of technologically oriented literature reviews, both area-specific [22, 39] and more generally oriented ones [32, 41, 70, 72]. In general, these take a technocratic, positive, and uncritical position with respect to the DT concept and application. Recently, however, some reviews taking a more critical stance have also emerged [32, 46]. This is largely related to the expanding of the use of the DT concept beyond relatively simple technological man-made systems towards broader, complex, and historically developed systems such as ecologies, humans, social systems, or cities. These reviewers have problematized two related sets of issues. The ontological one is a heightened emphasis on the asymmetry between the twins: the digital side will always be a reduced projection of the material original, a bunch of measurable properties, that are selected to serve a particular purpose. Like with any model, there exists a danger to become blind to this and to start to believe that the digital model is really equal with the material one. In a comparable context of infrastructuring, Parmiggiani and Karasti [59] bring forth the challenge of visibility – what data we collect and use in the analyses – and invisibility of the algorithms that analyse the data. In their example of Arctic Sea, the marine environment was turned into data with algorithms (which are invisible and complex), which determined what turned out visible, i.e., relevant, and what invisible, i.e., irrelevant; for example, marine mammals were excluded from the models, and thus made invisible for any further considerations. This leads us to the other set of issues – that of politics and power. As expressed by Korenhof et al.: "(...) *the digital substitute may change relations and power distribution between existing stakeholders and may give rise to new power relationships and stakeholders.* (...) *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.*" [[38], p. 1763-1764]. In the case of ecological modeling for a follow-up of a technology project discussed by Parmiggiani and Karasti [46] it was known that marine mammals were distressed by the technologies used at the sea, and that had been protested by environmental activists. When mammals were excluded from the models, their "voices" – and voices of those activists protesting for them – were silenced.

In our literature review on DTs published in HCI forums we are particularly interested in the potential criticality of the papers, because we feel that HCI could give a significant contribution for the future development approach of DTs both at the conceptual level (what is a DT and what can DTs be used for) as well as at the practice level (how should we develop DTs) – an approach that would be sensitive to the criticism discussed above.

3 METHODOLOGY FOR THE LITERATURE REVIEW

Previous literature reviews on DTs have focused e.g. on definitions, application contexts, architecture, and components of DTs [70], properties, capabilities, and functions of DTs as well as related concepts [39], or industrial application of DT [41]. Our specific interest in this paper is to understand how the DT concept is currently used in HCI and design fields. For that purpose, we conducted a literature review of articles written in English across the *ACM Digital Library*, *Springer Digital Library*, and the journals *International Journal of Human-Computer Studies*, *Human-Computer Interaction*, *Design Issues*, *Design Studies*, *Design Journal*, and *International Journal of Design*. The selection of these sources was based on the authors' combined experience more broadly in HCI and critical design studies. Following an adapted version of the PRISMA guidelines [52], the first author began the review process with the identification phase (Figure 1) using the words "digital twin" or "digital twins" and "HCI" in the search queries with no publication year limitation. This resulted in a total of 52 research articles in the ACM Digital Library. Additional hits were found outside of the ACM Digital Library, 19 in the Springer Digital Library in INTERACT conference proceedings, and one in the International Journal of Human-Computer Studies. After removing duplicates in the screening phase, the total was 39 articles. In the eligibility phase, seven articles were excluded because they mention DTs as a sidenote only and do not provide relevant content for this analysis. Thus, the final dataset in the analysis included 32 papers.

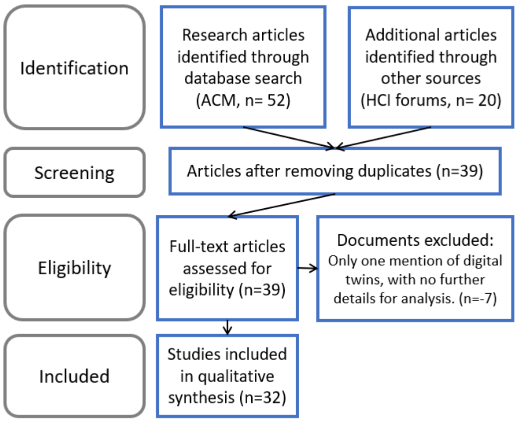

Figure 1: An adapted PRISMA diagram of the literature review process: identification, screening, eligibility, and final inclusion of selected articles.

Next, we collected information on how DTs were discussed in the articles, with an aim to understand how HCI researchers have used or envisioned DTs to be used so far. In practice, this information was collected into an excel sheet. First, we focused our analysis on the definitions of digital twins, i.e., a conceptual understanding of what a DT is. Then, we noted what purpose and domain (e.g., industry) the DTs were made or envisioned for in the dataset (e.g., product design, education, art). Regarding the purpose, we looked for what was the studies' stated 1) general purpose and motivation for the use of a DT, 2) industry-related purpose and motivation for using a DT, and 3) combined human- and design-oriented purpose and motivations for the DT use, as they were often difficult to separate. Moreover, we noted what other concepts were discussed in the papers (e.g., virtual reality, internet of things, etc.). In Table 3, we present the contexts and the viewpoints of the articles (design, utility, technical, and user engagement). As an understanding of DTs in HCI formed, we specifically considered the socio-technical viewpoint in the selected articles in narrating our findings – whether the articles somehow considered topics such as participation, inclusion/exclusion, empowerment, etc. The first author made the initial analysis of the papers. The first and second author collaboratively continued the analysis and then shared the findings with the other authors, who joined discussions about the findings and their meanings in the context of HCI research.

4 FINDINGS

4.1 Descriptive analysis

Table 1 provides an overview of the publication years of the papers in the dataset, showing that the publications began to appear after 2018. Since then the number of papers mentioning DTs have been growing in the HCI field. This follows the general trend of papers about DTs (see [32]) but the number of papers is still low compared to those with a more technical focus.

Table 1: Selected articles by year of publication

Year	n	References
2018	1	[83]
2019	9	[3, 13, 19, 33, 40, 50, 53, 58, 86]
2020	14	[4, 18, 24, 25, 31, 42, 48, 60, 61, 65, 66, 73, 81, 88]
2021	8	[15, 56, 64, 68, 77, 82, 84, 87]

Table 2 shows the papers' division across different conferences and journals. INTERACT conference offered the most papers by far, and then CHI conference. So far, the selected journals offered only one paper on DTs.

In Table 3, we present an overview of how the papers in the dataset approached the DT concept. We have divided the papers according to whether they take a Design view (i.e., how DTs could be designed), a Utility view (how to use a DT to benefit a given stakeholder), or a Technical view (with the focus in DT technical development). Many of the articles in the dataset discussed technical elements (models, data, algorithms), and utility, i.e., possible uses for DTs. Some articles included design aspects, which were not always clearly separable from the technical. These articles addressed quite specific contexts (product design, maintenance, education, health monitoring, etc.). In fact, articles related to design presented specific cases rather than discussing how DTs or systems incorporating them should be designed in general. Many of the studies did not report any user engagement in the design process. Although some of the articles included only one mention of DTs, they were included as they equated the term they were using (e.g. 'model') with the concept of DTs. However, while some articles use the term Digital Twin, they do not always factor in the two-way data flow (i.e., they are closer to a Digital Model or a Digital Shadow).

4.2 Narrative synthesis of selected studies

The papers in our dataset can be generally divided into the ones that somehow utilize the DT concept and the ones that fleetingly mention DTs (e.g. one mention in the whole article) or incorporate the concept in the discussion section, particularly when developing models or discussing implications of other technology to the future of DTs. We also noted that other concepts often discussed together with DTs were virtual or smart, e.g. internet of things, artificial intelligence, augmented reality, and virtual reality. Clearly design related methodologies mentioned in the analyzed papers were speculative design [81], co-design process [61], and research through design [53].

4.2.1 Conceptual understanding of Digital Twins. DTs were described in the dataset as virtual representations of the physical world; objects, environments, or systems [3, 4, 19, 33, 40, 42, 50, 58, 61, 65, 83, 86, 88], including the human worker [33]. DTs have been considered for creating digital replicas of human bodies [18, 66], but also as a replica of the human mind or persona (representing people's personal preferences and ways of learning) [60, 73]. The analyzed literature discusses DTs theoretically as a part of some model, framework, or concept [60, 83, 86], describes efforts of empirical work [33, 53], or presents specific technological solutions

Table 2: Publication forums of selected articles

Forum	References
INTERACT - International Conference on Human-Computer Interaction	[4, 15, 18, 19, 24, 33, 42, 56, 60, 64, 65, 73, 77, 81, 87, 88]
ACM CHI Conference on Human Factors in Computing Systems (CHI)	[3, 25, 48, 53, 83, 84]
The Biannual Nordic Conference on Human-Computer Interaction (NordiCHI)	[31]
International Journal of Human-Computer Studies	[68]
ACM Designing Interactive Systems (DIS) conference	[81]
ACM/IEEE International Conference on Human-Robot Interaction (HRI)	[82]
ACM International Joint Conference on Pervasive and Ubiquitous Computing and ACM	[58]
International Symposium on Wearable Computers (UbiComp-ISWC)	[66]
EAI International Conference on Mobile and Ubiquitous Systems (MobiQuitous)	[13]
International Conference on Information Technology (ICIT)	[86]
Mensch und Computer (MuC)	[40]
ACM International Conference on PErvasive Technologies Related to Assistive Environments (PETRA)	[50]
International Conference on Advanced Visual Interfaces (AVI)	[61]

utilizing DT technology [13, 40]. A particular overarching aspect visible in the analyzed literature was the accumulation of massive amounts of data, emphasizing the need for better data management and reuse. Clearly, data is a pivotal aspect of all DTs, and particularly the accumulation of real-time data offers exciting future research and development opportunities.

4.2.2 General purpose and motivation for Digital Twin use. The DT concept comes from domains of engineering and manufacturing, and this shows in the literature review as that context is common within the dataset. Other contexts were visible too (see also Table 3): smart cities, automated driving, health, education, and crisis management. The uses for DTs are many; they were considered beneficial for manufacturing [25], data-driven product design [25], designing situated VR and AR visualizations without visiting the site [61], iterative personalization [53], shortening R&D processes [88], interaction technology [50], improved modeling of systems [83], and autonomous facilities [58]. In maintenance, using DTs has been considered regarding machinery, hardware, indoor facilities, and whole buildings [13, 40, 50, 61]. Generally, DTs were used as a tool to help understand the state of physical entities like the state of production [65], to support decision making [19], to support work in a restaurant [48], and to monitor progress of work [40]. In these instances, the DT yields benefit for the worker or a higher-level manager or facilitates remote work. DTs can be characterized as 'a bird's eye view' to inform decision making and collaboration.

4.2.3 Industry purposes and motivation for using DTs. In the industry context, DTs are used for making complex processes easier for humans to handle. DTs of products have been considered to have potential to help improve R&D processes through AI-based analysis and feedback [88]. DTs have also been considered helpful for analysis of urban services [86]. DTs can be combined with different technological solutions, such as head-worn-displays in restaurants, healthcare, and industry [48, 68] and drone technology [64, 82]. Moreover, DTs of offshore platforms have been developed for training and testing human-robot collaboration [58]. DTs are generated based on data of physical objects, so that humans can use them to maintain, manage, improve, and train. In the realm of automated driving, a model representing the driver, vehicle, and environment has been ideated [60]. Moving from DTs of objects towards human DTs has been considered, with acknowledgement of the challenges in making a comprehensive information model of the worker [33], but we are still in early days considering the human DT.

4.2.4 Human- and design-oriented purposes and motivation for DT use. From a design perspective, DTs have been labeled a tool for data driven design [25, 53]. The DTs of consumer products could be used for personalized items but also to provide data for the designer to develop a new product [53]. DTs of real objects that are hyperlinked to a physical network could be used to explore the design of physical of environments [42]. One study introduces the Corsican twin, named after Alexandre Dumas's novel (where twins were able to feel each other's distress), as their VR tool is meant to help designers create visualizations of physical environments with DTs, and then experience those visualizations in the real locations using AR [61]. There were also other applications of DT for physical environments to support creative design, like a 'home in the cloud' tool for interior design [84], and DT as a part of a human-AI co-creation model, where manifestations in the physical world are reflected in virtual form for exploration and analysis [87]. Regarding user perspective, DTs have been thought of as a way to enhance user interaction [19], and to create immersive user experiences based on data, scenarios, and simulations [31]. Technology applications in art exhibitions have included DTs, which can provide interactivity for the users [15].

DTs were used for augmenting human understanding and decision-making in relation to different spaces: in city development and management, with regard to stakeholders and designers shaping smart cities [81], making a model of the constantly evolving services [86], as well as interaction design in urban virtual landscapes [42]. In the domain of urban design, a framework has been ideated for interactions between smart cities and transhuman citizens – so

Table 3: Overview of how the selected articles approached the DT concept

Ref	Context	Design view	Utility view	Technical view	Engaging users	DT main focus of study	DT part of study	DT mentioned
[87]	AI creativity		x					x
[15]	Art		x					x
[60]	Automated vehicles	x		x		x		
[3]	Crisis management	x	x					x
[82]	Drone AI	x	x	x		x		
[64]	Drones	x	x	x			x	
[57]	Education		x					x
[77]	Games, IoT	x	x	x	x		x	
[18]	Healthcare		x	x	x	x		
[68]	Healthcare		x					x
[66]	Healthcare	x	x		x			
[83]	Industrial systems	x			x			x
[58]	Industry, offshore	x	x	x		x		
[84]	Interior design		x				x	
[73]	Learning engineering	x	x				x	
[24]	Learning engineering	x		x		x		
[19]	Manufacturing	x	x	x		x		
[33]	Manufacturing	x	x		x	x		
[65]	Manufacturing	x	x		x	x		
[13]	Maintenance	x	x		x			
[50]	Maintenance		x	x		x		
[25]	Product design	x	x	x	x		x	
[53]	Product design	x	x	x			x	
[88]	Research and development	x					x	
[48]	Restaurants	x	x		x			x
[40]	Remote work	x	x	x	x			
[4]	Simulation training	x	x	x			x	
[51]	Smart cities	x	x	x	x	x		
[86]	Urban services	x	x		x			
[81]	Urban design		x					x
[42]	Urban landscape design	x				x	x	
[31]	Virtual reality	x	x		x		x	

people can engage and influence decision making [81]. The DTs were also considered to be useful for human collaboration, where DTs of locations as shared information spaces help share responsibilities [3], or provide a shared understanding of an environment – e.g. for emergency response [4].

Even though modeling humans in general is considered challenging, DTs of individual humans have been considered for various purposes in the healthcare context (monitoring [66], prediction, and detection [18]) and to provide individually tailored responses from software, to a driver [60] or a learner [24, 73]. Use of DTs for detection of gestures and their interpretation has been used as a tool for reducing inequality of blind and visually impaired people [77]. DTs have been envisioned to increase user engagement through more immersive user experiences [19, 31, 42]. DTs of humans can represent physiological data, i.e. the human as an object. One such example investigated the use of DTs to predict individuals' stress levels in extreme environments based on data of the human body and the environment [66]. DTs of elderly people have been envisioned to help the doctor see the overall wellbeing, predict and detect problems, but also help explain the situation to the patient and provide personalized third-party services [18]. This article also pointed out the possible empowerment ofthe patient through self-tracking, as well as the potential risks in such a detailed DT of individuals, e.g., considering privacy. DTs of humans can also represent the non-physical aspects of individuals. One example would be the learner model, a DT of the human learner in Adaptive Instructional Systems that aim to provide tailored instruction and recommendations based on accumulating data [24, 73]. The learner model is meant to represent the real person and the environment, including physiological and behavioral data, knowledge, abilities, habits, and other attributes related to learning [26, 77]. The authors discuss the DT of a learner as imperfect because of the challenges in observing the mind and the limitations in the scope of data [26]. Another way to link DT to learning has been done by using a DT as an AI based tool that can be used in building collaboration between humans and machines in teaching and learning [56]. While the DT of a human as an object is envisioned for healthcare purposes – comparable to maintenance of buildings – the non-physical DT is a way to provide personalized and optimized learning for an individual. The challenges are different, and so is the intended user.

5 DISCUSSION

Our focus in this study was on systematic understanding of the recent state of the art in HCI and design fields regarding use of the DT and how HCI could conceptually address design challenges arising from the characteristics of DT. This study contributes in the following ways: First, we provide a systematic overview of the research by analyzing 32 empirical studies. Second, based on our analysis of the studies and building on the characteristics of DT, we propose a conceptual approach to DT together with potentially useful HCI perspectives to DTs, allowing a critical look to them. Next, we discuss our contributions in further detail.

5.1 Overview of the findings from the empirical studies

Study of DTs is an emerging area of research in HCI: all 32 papers were published in 2016 or after and 66 percent of them 2020 or after, which signals the novel nature of the topic. Our analysis of the literature shows that so far HCI researchers in this dataset have not paid particular attention to the data-driven nature of DT and its implications to DT design and operation, including politics of design regarding DTs. To summarize, DTs are investigated in our dataset within the manufacturing industry, emergency response, smart cities, learning systems, and for different types of designs. DTs originate from digital models of real-world physical objects – initially static, then animated through data feeds to present the current state of the object and finally realizing their potential as technical solutions that can predict or simulate behaviour and events and having a feedback link from the digital to physical. This allows state adjustments in real-time and planning for events proactively – i.e., influencing the physical world. The current research foci naturally reside over areas where observation and anticipation of state and events of a physical object is of interest, such as various industry use cases and, increasingly, modeling and simulating the human body. In our dataset, the DT was treated mostly as a useful tool for a specific purpose in various contexts, often somehow augmenting and helping humans in their tasks or interests, delivering useful information, enhancing user experience, or supporting collaboration or information flow between people, but it did not venture further into DT potential for inclusion or its inherent characteristics that can lead to exclusion: that a DT is built using a limited number of variables and that a deep understanding of the modeled phenomenon is needed ([25] lightly touching this). With respect to the two strands of criticism on DT in general, the discussion on DT in HCI is thus becoming aware of the issues related to modelling and limitations of the digital part of the twin, but the discussion on politics and power related to DT is still largely missing. We propose this as an area where HCI can contribute, for example through the political PD perspective (see e.g. [8]).

There were also initial intentions and ponderings already on the uses of DTs beyond the mere tool view, looking beyond the current paradigm of “model of objects” and into exploiting the DT as a concept in novel ways in the realms of education [24, 73], smart city [42, 81, 86], or data visualization [61]. Examples include making citizens’ involvement in decision-making possible in the context of smart cities [81], using a digital solution for making the world more equal for the disabled [77], and empowering patients through their better understanding of their personal health data [18]. Still, there were no discussions on how DTs could either increase inclusion by raising visibility of something or someone, or cause exclusion by making something or someone invisible, for example by leaving them out of the digital models like marine mammals in the Arctic Sea [59], or through algorithm design. Quality of the data used in DTs was brought up in some papers [24, 25, 53] but generally we can say that there is a lack in this dataset related to considerations on the fundamental characteristics of DTs. Those make DTs very powerful but at the same time also cause inherent weaknesses in them, which can result in exclusion through limited views to a phenomenon, limited data of it, or its limited understanding. In other words, some voices can be silenced, preventing a true dialogue. We argue that this is something that HCI research should pay attention to, and we will discuss that next.

5.2 Facilitating further discussions: implications of the DT characteristics to HCI research

Technology has a major role in how people can take part in today’s society, be it decision-making or everyday life’s activities. Therefore, inclusion should be considered in all technology development. Technology is not just about creating equipment and tools – it creates solutions that either help or hinder us, sometimes doing both at the same time. Every technical solution created should thus be considered, not as technology, but as a socio-technical system [7] and its design should consequently take all relevant aspects into account, from legislation to needs of users, to sustainability and ethics. This implies multi-disciplinary viewpoints in design, but it also means we need mental constructs that help to tie in the different viewpoints during the design process [37]. Although these themes have been touched upon in a number of papers in the literature review, there is clearly a lack of common vocabulary and common conceptual framing to enable the converging and cumulation of results.

We posit that one way forward to expanding DTs’ utility beyond the current state of the art is to not view them as mere technical solutions, but transcend the thinking and consider the DT as a conceptual construct that gives us a handle to a real-world entity – be it an object, a process, or even a complex phenomenon, and that DTs have potential to give voice and help us to come even to a ’dialogue’ with those. With this in mind, to facilitate further discussion, we propose five dimensions for the DT as a conceptual construct (Figure 2), based on the shared characteristics of DTs, as discussed in section 2 related to the DT concept and identified as a common ground between most of the work analyzed in this article. While these dimensions arise from a DT as a technical construct, they attempt to capture the essence that HCI experts should be aware of in order to have a critical look at the DT as a construct, and to be able to consider how HCI perspectives and approaches can be used in further design of DTs. Next, we discuss those dimensions and propose potentially useful perspectives to be used when designing a DT from HCI perspective.

5.2.1 The first dimension: data-driven nature of DTs. An example of datafication [49], a DT is a digitized representation of an entity, built on data from the real-world. However, in many cases the captured data can have low technical quality – it is too sparse, has gaps, is of wrong type, has a statistical bias, or some data is missing altogether [12]. This is a problem for the DT similarly to all data-driven technologies. The challenge of technical data quality has been widely acknowledged and can likely be resolved with technical solutions given time. However, there are also other data-related issues that need to be resolved, especially where a DT is intended to be used to model societal functions or human behaviour. One question that the world has already ran into is ethics – if people are monitored in the wild, who owns the data, how to manage consents and make users aware of the possibility of the (re)use of their data? Regulatory reactions such as the European Union General Data Protection Regulation (GDPR) are clear indications of the importance of this issue. The second issue is data bias – Schwartz et. al [69] consider that besides statistical and computational bias, i.e., technical data challenges, there are also two other types of biases that can affect both data and the interpretation of it – systemic bias where the data tends to reflect the (assumed) 'norm', and human bias where individuals and groups both provide data and interpret it based on their perceptions and values, which rarely are objective. While they are focused on bias risks regarding AI, the same issues are relevant for any data-driven model and underline the need to view a DT design as a socio-technical construct, rather than a mere technology when designing, developing, deploying, evaluating, using, or auditing the solution.

For this dimension, focus on data quality is an obvious need but particularly weeding out non-technical bias is something where HCI approaches can excel. We thus propose considering how user-centered design methods can help with data quality and the different versions of data bias. PD practices, for example, can help extending the understanding of the data through participatory design process, where users of DT, the ones data is collected from, and those affected, are all treated as experts who understand the actual real-world process. This can be supported with the information infrastructure/infrastructuring thinking from PD (e.g. [35]) that draws attention to design as "*a process of inscribing knowledge and activities in new material forms*" [[36], p. 21] and reminds that data is grounded in the situated real-world context. With the next dimension, the significance of context is discussed further.

5.2.2 The second dimension: each DT has a one-to-one relationship with an individual instance of a specific real-world entity. In an engineering view to the world, the focus is often put on the system being created. What easily follows is that the uniqueness of the real-world entity is acknowledged, but the context in which it operates is ignored, considered to be trivial, or more or less "the same" in all instances. Yet, just as a DT is always a manifestation of a single, unique entity, the contexts for these entities are always unique to each DT. Furthermore, there is an interplay between the DT and its context. Even if we were to have two objects that are created completely similar – hence the DTs of these two objects are the same in the beginning – both objects will start to differentiate from each other when placed in a different setting and/or having somewhat different usage. Without knowledge, i.e., data, of these influences and interaction, past or current, the (human or AI drawn) conclusions from the real-world data can be off, even significantly. We therefore argue that the context plays an important role through its effect on the real-world entity and can contain important information for interpreting the data from the entity itself.

We propose HCI designers to consider what effect context has to a DT. PD excels in "located accountabilities" [75], reminding that the solutions should always be understood in their actual settings [26]. PD tools and methods (e.g. [71, 74]) can help identify critical interactions between the entity and its context, thus creating a more complete DT design. Of course, this is not always straightforward, as inclusion of additional real-world elements increases the technical complexity and cost of the overall solution, and there may also be limitations in including an identified interaction if the influence mechanism is not known and hence cannot be modelled. The context may also change over time, thus even if the initial context is taken into account in DT design, changes may make the design obsolete. Therefore, in addition to generally acknowledging and examining the context of a DT carefully and critically, we propose also widening the understanding of what is a context for a DT through Dourish's thoughts about context [20] – seeing context not only as something that can be described as a set of "descriptive features" but also from the perspective of practice – what actually happens in that setting, how the action is situated [75]. Thus, when designing a DT, in addition to the context we need to also consider the related practices, not only the more static, descriptive features of a setting. To sum up, we need to see the context (features of the setting and the linked practices) of a DT always tied with the unique DT and to acknowledge the potentially changing context both in DT design as well as in its operation.

5.2.3 The third dimension: a DT has dynamic interaction between the physical and digital. The digital object gets real-time data from its real-world twin and, based on it, drives actions that impart changes to the physical world. While designing this feedback loop does not necessarily benefit of the HCI approach more than any system development does, the challenge is in understanding how the imparted changes to the physical world alter the situation down the road and how that should be taken into account in the design, in particular if the DT has more advanced features such as AI models for prediction. Real-world entities change over time – whether from within, or due to changes imparted by their context – and this can mean the AI models run by a DT become inaccurate, or even invalid (cf. data footprints [17] and trajectories of data [9]). This is an issue to DTs and to data-driven intelligent augmenting technologies in general, since as of now the models used for their deduction logic are predominantly static. They have an in-built assumption of how the world operates and how this is reflected in the data, and they are bad at coping with changes. Yet, the more the new intelligent systems make headway to our life, the more complex and dynamic environments they encounter, and they need

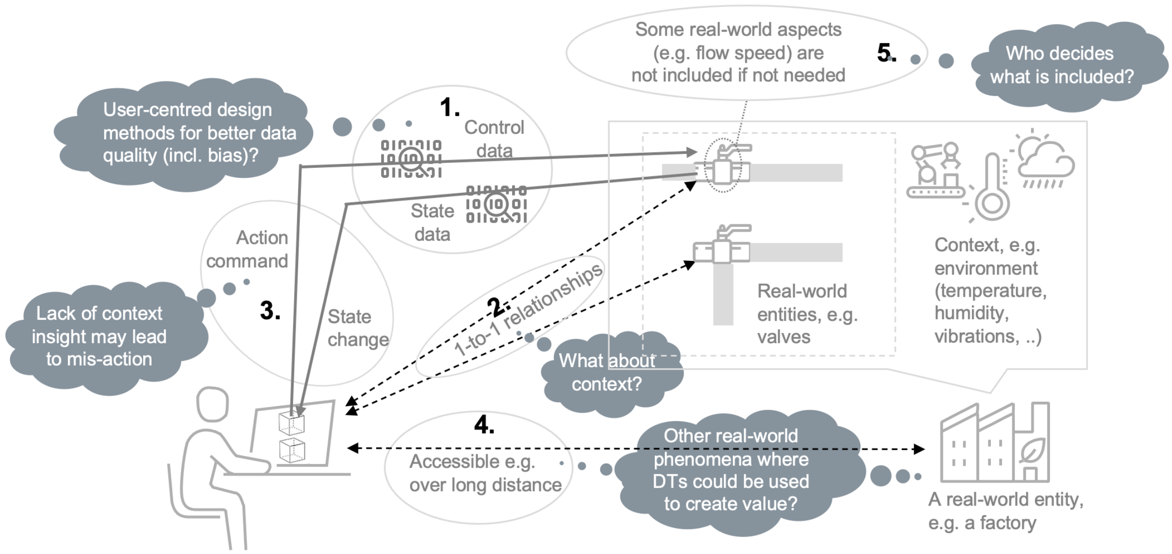

Figure 2: Dimensions for the DT as a conceptual construct: 1) Data-driven nature; 2) Each DT has a one-to one relationship with an individual instance of a specific real-world entity; 3) A DT has a dynamic interaction between the physical and the digital; 4) A DT creates value by making the real-world entity more accessible for stakeholders; 5) A DT is not a complete copy of a physical world entity.

Table 4: Dimensions for the DT as a conceptual construct: proposed research areas where HCI can contribute and links to previously identified research gaps

#	Dimension	Proposed research areas for HCI to contribute	Link to previously identified research gaps
1	Data-driven nature	How user-centered design methods can help with data quality and different versions of data bias	Support from existing and future standards; Collection, storage, and sharing of data used by DTs; Seamless integration of DTs
2	1-to-1 relationship with an instance of a specific real-world entity	Effect of context to a DT; Widening the understanding of what is a context for a DT; Link between a unique DT and its context both in design phase and in operation	Support from existing and future standards; Seamless integration of DTs
3	Dynamic interaction between the physical and the digital	How the DT is capable in reacting to the change in either the entity it models or the context of the entity; How the principles of context- and practice-sensitive approaches can be applied for dynamic and adaptive solutions that may need to automatically adjust their operation during their operative lifetime	Lack of understanding on requirements across the entire product life-cycle; Support from existing and future standards
4	Value creation through making the real-world entity more accessible	Exploring use of DTs for novel and existing contexts with value creation perspective; What data can used for the DT; how the data is created in these novel contexts; To whom or for what purpose the DT generates value, and what happens to those who are left out of the model	Cost-benefit analysis and where DTs are beneficial; Support from existing and future standards
5	An incomplete copy of a physical world entity	Link between DT purpose, available data, and quality of data; Who are the experts in choosing the variables for a DT; Who is given power in DT design and why; Taking a more complex view to data for the DT	Support from existing and future standards; DT fidelity

the capability to continuously learn, forget, and adapt, even to abrupt changes.

Thus, for this dimension we propose focusing on examining how the DT is capable of reacting to the change in either the entity it models or the context of the entity. This could be a future research direction for HCI, for example to investigate how the principles of PD (see e.g. [43]) and other context- and practice-sensitive approaches could and should be applied as design approaches for solutions that are dynamic, adaptive, and may need to automatically adjust their operation during their operative lifetime. Or, in accordance with the principle of changing the future, how HCI could use such systems in order to make the world a better place to be.

5.2.4 The fourth dimension: a DT creates value by making the real-world entity more accessible for stakeholders.

Datafication effectively removes the real-world constraints of an entity, turning it into information that a stakeholder can then put into use. A DT could also serve multiple stakeholders in parallel and independently, providing each of them a unique, tailored view to the real-world entity, based on their needs. This allows each stakeholder to pursue their interests involving that entity more readily. The value is created in DT through varied mechanisms depending on the interests, e.g. by providing visibility to current state, creating possible future scenarios, or allowing interaction with the real-world entity. As the DT concept is currently largely tailored for industry use, due to its heritage, the gained value includes process optimization, asset monitoring and controlling, help in decision-making, real-time prediction, etc.

Here HCI can widen the perspective of DT application and who are the stakeholders and what the interests – i.e. value – may be. We propose exploring use of DTs for novel (and existing) contexts with value creation perspective and having an open mind with what kind of data could be used from that context and how that data is created (are there maybe new ways to create data). Even as a desk exercise this would increase our understanding of what is the true potential – and pitfalls – of DTs in modeling our world. User-centric value creation is an obvious opportunity for DTs (explored in [18]), and the DT could be used as a tool for capturing usability data to optimize for greater user experience and other aspects pivotal in HCI. So far DTs have considered some data that is integral in HCI (usability [61], user experience [19, 31]). Going beyond product development, there is also an opportunity to explore DTs creating value even in wider contexts and purposes beyond the areas easily measured with sensors, such as nature, art, mental health care, citizen, or employee empowerment, reducing the digital divide, or phenomena like work well-being, racism, and gender equality. Some of these are already identified in our literature review data set, such as learning [24, 73], empowerment of the user [18, 66], and interactions between cities and citizens [81]. Framing a societal phenomenon as a DT allows technology developers to grasp and work with the phenomenon in question, using structures and concepts they are familiar with. Likewise, as DT as a concept aims to mirror a real-world phenomenon, it is more concrete and relatively intuitive to understand, thus making it easier to work with by non-technical people, such as end-users. This gives way to increased user empowerment as well as designer empowerment, and as such could be a tool for HCI.

Regarding stakeholders, this is very much a question of power and politics of design: we propose also asking to whom or for what purpose the DT generates value, and what happens to those who are left out of the model, either intentionally or unintentionally. Because of that we argue that it is central examine who gains value, how, and why, and who does not gain value, and why. To support the value creation perspective, we suggest trying out the PD notion of "institutioning" [30] that could yield new insight here when combined with value creation, as it frames the design process as dependent on "various institutional frames, which can, conversely, directly and/or indirectly lead to changes in a variety of institutional frames" [30], stressing that a design process is dependent on institutions – such as democracy, dialogue, or policies – at micro, meso, and macro levels.

5.2.5 The fifth dimension: a DT is not a complete copy of a physical world entity.

Although a DT aims to be a faithful representation of a real-world entity, creating a 1-to-1 copy is not realistic in most cases, hence some aspects are always left out. This brings up two important issues to consider when designing and utilizing a DT. First off, the choice of what variables are included and what is left out is critical when designing a DT. Variables need to be relevant from the DT functioning and value creation point of view. Related design challenges identified in our dataset include data-driven product design [25, 48], building human-machine interfaces [60], or user interface design in DT context [66]. Selecting the right variables requires deep understanding of the physical world entity, what things affect it, how it works, and how it can be controlled and managed – but also understanding of all the relevant stakeholders and their interests. As the selection is done by DT designers, the question becomes who are involved in designing the DT. Subject matter experts from specialists to users to affected are required to create a good, value-adding DT that is fit for purpose. The more complex the case, the more multi-disciplinary design team is likely needed. Secondly, the stakeholder utilizing the DT needs to be aware that the information is inherently partial and may miss an important aspect, such as context. They therefore need to take a critical stance towards the technology, always being ready to ask, "is this the full picture" and ready to investigate issues further, not just accepting the story as told by the DT.

Here is then the traditional technology development challenge that HCI is well-equipped to tackle, leveraging the existing strengths of user participation, interdisciplinary collaboration, and research on human behavior and sociology, as well as methods for understanding humans through for example ethnography. An interesting angle to this would also be the historical 'data footprint' of objects (see [17]) or 'trajectories of data' that combine the physical and digital, examining and supporting the intended, actual, and retold (cultural) 'stories' [9], as they both view data from different perspectives through different actors and contexts, thus making the relative nature of data, rather than absolute, clearly visible. This calls for also asking the core question of PD and human-centered design more widely: who has the power in the design process – who the experts are we should listen to when trying to understand how a DT should be built and what variables to choose.

Thus, in relation to this dimension, we propose paying attention to the following when designing DTs: When selecting the variables for the DT, carefully considering what the DT is used for; what data is available; what is the quality of the data; is there a risk of e.g. a bias; who are the experts to be consulted and listened to when choosing the variables (i.e., who understands the phenomenon widely enough); who is given power in DT design and why; and can we take a more complex view to data for the DT, acknowledging its relative nature.

Interestingly, the five dimensions for the DT as a conceptual construct identified in the current study can be linked with the research gaps identified by Jones et al. [32] in their more technically oriented literature review of DTs (see Table 4). The first gap, need for a cost-benefit analysis of DTs and where DTs are beneficial, can be linked with the high-level aim of the current paper to gain a better understanding of how DTs could be beneficial outside of the existing use cases, as well as with the fourth dimension related to DTs creating value. [32] also identify a lack of understanding related to the requirements for DTs of physical products across the entire product life-cycle. This can be linked with dimension three, dynamic interaction of physical and virtual – DTs' capacity to react with the changes in the context of its physical counterpart. The third gap is related to how the existing and future standards support DTs. This gap can be linked with all dimensions identified in the current study, as all of them can be affected by standards that govern DT use. [32] also bring forth the level of DT fidelity, which has a straight link to dimension five: how complete a copy of the physical twin it is possible or feasible to try to create. Collection, storage, and sharing of data used by DTs (data privacy issues, who owns the data, etc.) was identified by them as the next research gap, which can be linked with dimension one, the data-driven nature of DTs. Finally, [32] note the potential problems related to seamless integration of different DTs together. This can be linked with dimension one but particularly with dimension two, which tells us that context of the DT is important – if we want to link different DTs together, we need to understand each of those DTs in their own context. We call for future work for establishing the dialog between the more technically oriented agenda points and characteristics of DTs identified in previous research and the HCI-focused proposals presented in the current study. As Jones et al. [32] note, DT research would benefit from linkage with similar and connected fields.

6 CONCLUSIONS

Our literature review gives an understanding of the current state of the art regarding DTs in HCI, showing that HCI researchers have already started to work with DTs but have not yet incorporated many HCI principles with their work. There is also a lack of HCI research focusing on data-driven approaches for DT development. However, DTs have potential to help us with everyday activities and decision-making. Considering this, we see this paper as a conversation starter in what HCI can bring to design of DTs. We believe that the DT is a 'concept of the future' and that HCI approaches can help development of this concept in order to DTs give voice to the silent as well as silenced ones, and opening our eyes to see beyond invisible (cf. [59]), in the spirit of UNSDG 10. DTs are currently largely being used within industrial contexts and with purely objective, sensed data. We call for a critical, context- and practice-oriented perspective to DTs in HCI that takes politics of design seriously in the design and development of DTs. We see the potential in DTs, but we want to remind of the risks related to datafication and of the need for a human-oriented view to DTs. Thus, we propose approaching DT as a conceptual construct with five dimensions that are based on the shared technical characteristics of DTs and suggest HCI esearchers and practitioners to critically consider all these dimensions when 1) examining a phenomenon/a real-world entity that might benefit from creation of a DT of it; 2) when planning and conducting their design work of a DT; 3) when evaluating DTs and analyzing their effectiveness. We want to also remind not forgetting the 'blindness' of DTs to everything that has not been included in the Digital Model for a DT, as that is a weakness of DTs, similarly as of any model or simulation of a real-world entity.

Our study is limited by the possibility that we missed some papers by using "digital twin" as a search term, as some studies might discuss the same concept with different terms [67] since the terminology has not been definitively established yet [66, 67]. We also focused on a limited set of forums appropriate to our interest in the state-of-the-art in HCI and design fields, thus leaving out many forums that potentially discuss DTs, which limits our findings. We also sometimes needed to make interpretations, as it was not always obvious how to classify the papers. For future studies beyond the discussions above, we propose linking DTs with the discussion on the nature of artefacts and objects through ecologies of artefacts [34], as we think it could also open new avenues to the conceptualization and use of DTs.

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