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Human-Centric Digital Twin: A Transdisciplinary View

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Abstract. Due to the rising digitalization in the past few years, even more data can be collected from smart products and sensors to describe the real world, goods, environments, and newly humans including those mutual interactions. Digital twin (DT) has become a key word in engineering, society, and medicine, which is also a hot topic in research for creating virtual data-driven replicas of real objects and simulating their behaviors to predict and optimize the entire system functioning. DTs can mirror the physical entities throughout their lifecycle and create real-time connections between the physical and virtual worlds to monitor and control physical objects from any location. Physical objects can be any living or non-living object, such as humans, machines, robots, cars, buildings, plants, food, or economy. Numerous papers related to DT in various industries have been presented, but very few are focusing on the human-related aspects and the quality of the human machine interaction. In this context, how to shape a human-centric digital twin (HCDT)? The paper states the needs of a human-centric approach in the design and development of DT and presents a set of significant applications of HCDT in different fields, from industry to medicine, from economics to society, discussing the positioning of the HCDT concept in the landscape of transdisciplinary engineering, which is also subject of a workshop during the conference.

Keywords. Human-centric approaches, Digital Twin, Human-machine interaction, Transdisciplinary Engineering.

Introduction

The idea of the Digital Twin (DT) refers to the generation, maintenance, and operation of the virtual replica of a physical object, product, or system throughout its entire lifecycle. The purpose of this concept is to define, verify and validate a product or a system with a high fidelity including all its characteristic behaviours, input/output data flow, and failure scenarios. The physical system can be monitored with its DT by collecting and processing real-time data, and (possible) issues can be identified early, communicated with the physical system, and addressed as necessary [1].

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Coming from the area of digital factory and Industry 4.0, the core of DT strategy is the tight integration (“fluid transition”) between virtual and physical worlds, that permits to achieve greater efficiency and competitiveness. From a practical point of view, the biggest challenge of industrial DT is about the definition and implementation of holistic models and architectures able to effectively integrate the digitization into the factory shopfloors [2]. Today the focus is on the technological enablers for the interconnection and cooperation of different production platforms and resources, based on computational intelligence and control logic, which are no more centralized in a single location, but distributed all over the network [3].

DT undoubtedly represents one of the major innovation trends of the modern era and offers a unique way to involve both the research community and industrial players to define common standards, architectures, and approaches across different sectors, in order to make societies fully benefit from the advantages related to digitization, according to a transdisciplinary perspective. DT has many fields of applications, such as product designs, product service innovations, smart manufacturing, and building information management. Overall, DT is considered an important aspect of the company digital transformation, by enabling effective and valuable data sharing between the real world and its virtual replica [4].

Up to now, a lot of proofs have been realized to demonstrate the feasibility and the advantages of such a digital-driven view, but several issues still need to be solved as also reported by [5]. There are two main open issues in DT implementation: (a) the lack of standardized and universally recognized methods and tools to implement DT into real environments, and (b) the absence of human-related aspects into the DT, for instance, how DTs as autonomous systems interact with humans. Such issues discourage companies from planning investments on the adoption of DT solutions, even when the acquired systems incorporate sensors and communication capabilities. Indeed, the lack of standardization strongly limits the system interoperability, while the lack of human factors does not permit to fully represent those processes where human-machine interaction plays a crucial role (e.g., system control, precision assembly, system maintenance, human-robot collaboration, decision-making) [6].

While DT technology is still in its infancy and lacks maturity, it has only been partially adopted in practice, with some tasks still being handled by humans. Moreover, although the term "digital twin" implies an automatism, its interaction with humans is mostly necessary, for which suitable user interfaces are created. These user interfaces must be designed in such a way that the user can collect the necessary information and data from the system (status messages, results of simulations, etc.) and carry out the necessary actions without much prior knowledge. A distinction must be made between the different roles and user groups. Then, a separate interface must be provided for each user group, as a single interface for all users would be overloaded with excessive information. Accordingly, every employee needs an interface that provides the relevant data and information for a specific task. Practitioners frequently ask what duties (or functions) are to be assigned to DTs in a work system and how the work system might affect humans because of this piecemeal application of DTs [7].

In this context, this paper discusses the concept of human-centric digital twin (HCDT) which is inherently transdisciplinary, stating the needs of a human-centric approach in the design and development of DT and reporting a set of recent prototypal applications of HCDT in different fields, from industry to medicine, from economics to society. The outline of the paper is as follows. In section 1, the background of DT with its taxonomy and the transdisciplinary approach is introduced. In section 2, the recommendations for implementation of HCDT in different fields (e.g., industry, medicine, economics) are described by use cases. In section 3, we discuss the challenges that still exist in the different domains and provide some conclusions. This paper is linked to a workshop organized within the TE2023 international conference to discuss the topic according to a transdisciplinary perspective and provide new insights in the field.

1. Possible applications of Human-Centric Digital Twin

In research and practice, many types and expressions of DT can be found for a plethora of use cases along the product lifecycle within Product Lifecycle Management (PLM). Three definitions of DT can be identified: 1) the Digital Master, 2) the Digital Manufacturing Twin, and 3) the Digital Instance Twin. These definitions represent the different phases of a DT, respectively design, manufacturing and exploitation [7]. DT examples can be found in a vast array of domains, where the simulation of the real systems' behaviours can be used for different purposes: from prognostic and problems' detection [8], to definition of optimized manufacturing system control strategies [9], ergonomics analysis [10], until creation of high-fidelity virtual models and virtual commissioning [11] or integration of operators in the digital simulation loop [12].

For comparing and distinguishing specific types of DT, an appropriate taxonomy is necessary [13]. In order to adopt a holistic view and refer to DT in very generic way, across the disciplines according to the transdisciplinary approach [14][15][16], we have selected dimensions that may apply also to other domains than manufacturing (Table 1). These dimensions are selected to support comparison between different domains in the second part of this paper.

Table 1. Taxonomy of Digital Twin, derived from [13].

Dimension	**Characteristics**			**Exclusivity**
Data link (DL)	One-directional (OD)		Bi-directional (BD)	Mutual
Purpose (P)	Processing (P)	Transfer (T)	Repository (R)	Not
Accuracy (A)	Identical (I)		Partial (P)	Mutual
Synchronization (S)	With (W)		Without (W/O)	Mutual
Data input (DI)	Raw data (R)		Processed data (P)	Not
Time of creation (TC)	Physical part first (P)	Digital part first (D)	Simultaneously (S)	Mutual

The dimension data link specifies how communication between the DT and its physical counterpart takes place, which can either be one-directional or bi-directional and is, therefore, mutually exclusive. The way of handling data by a DT may have three, not mutually exclusive, characteristics: 1) processing data such as monitoring, analysis, forecasting, or optimization; 2) transfer data from one point (e.g., the physical part) to another one (e.g., a data warehouse); or 3) data repository. Model accuracy concerns the accuracy of expression of the physical object in the digital representation: either by an identical accuracy or a partial accuracy and is mutually exclusive as well [13].

The dimension synchronization consists of two characteristics: 1) active synchronization between the DT and the physical part by (real-time) data updates during its lifecycle, or 2) without synchronization, and is mutually exclusive. The dimension data input differentiates between raw and processed data, which can be data received from sensors or databases, or pure or raw data gathered directly from sensors or other data collection devices. In addition, data might be used that are pre-processed (e.g., by analytic software) before it is transferred to the DT. Data input is not mutually exclusive [13]. The dimension time of creation distinguishes between three characteristics determining the chronological order in which the respective parts of a DT come into existence. Therefore, the dimension distinguishes whether the physical part or the digital part is developed first, or both parts are developed simultaneously. Most DTs are designed after a physical system has been created [13].

In order to describe how HCDT can be created in the different contexts of application, we need to define a reference framework where human-system interaction is included into the digital loop and humans become data generators / users according to the proposed taxonomy, similarly to machines (Figure 1). Indeed, real environments and people could be sensorized to collect data about humans and provide data to humans, thanks different types of interfaces, according to the model proposed by source [12]. In this framework, human roles can be described as presented in Table 2. For each role a dedicated set of functions is assigned to describe the interaction between the human and the DT.

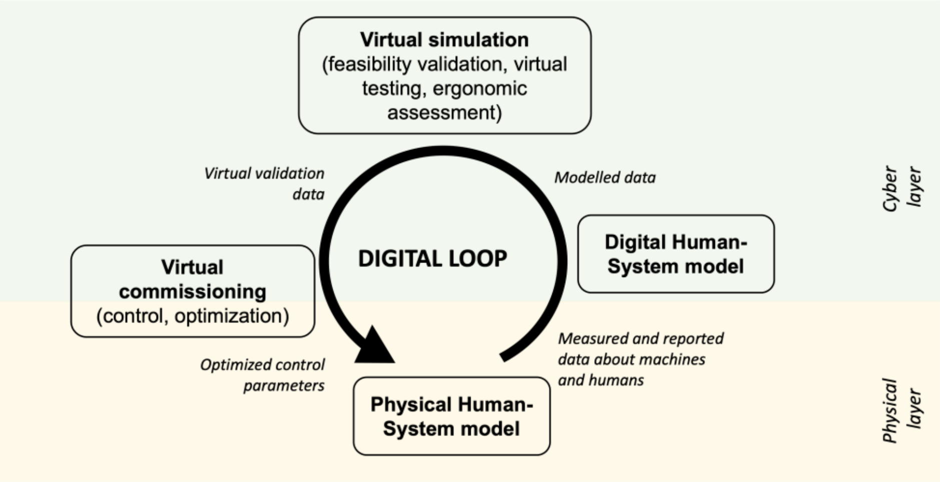

Figure 1. Human-centric Digital Twin framework.

Table 2. Functions expected to be conducted by different roles, derived from [7].

Operator	Worker	Planner	Consumer
• Sensing • Representation • Description • Communication • Control	• Physical action • Actuation • Communication • Control	• Description • Planning • Prediction • Interpretation	• Sensing • Actuation • Communication • Interpretation
Decision maker	**Policy maker**	**Patient**	**Nurse**

Operator	Worker	Planner	Consumer
• Optimization • Simulation • Forecasting • Prescription	• Analyze and Monitor • Simulation • Forecasting • Prescription	• Sensing • Actuation • Communication • Control	• Sensing • Analyze and Monitor • Forecasting • Prescription

If we create the relationship between a human role based on functions described in Table 2 and the dimensions described in Table 1, then we will get a matrix as highlighted in Table 3. With regard to dimensions shown in Table 1, the roles discover different functions, apart from the different field of applications where DTs are used.

Table 3. Human roles vs. dimensions within Human-Centric Digital Twin.

Roles	DL	P	A	S	DI	TC
Operator	OD	P	I(P)	W	R	D
Worker	BD	P	P	W/O	P(R)	D(P)
Planner	N/A	T	I(P)	W/O	R	D
Decision maker	OD	R	P(I)	W/O	R	P
Policy maker	OD	R	P	W/O	R	P
Consumer	BD	P	P	W/O(W)	P(R)	D
Patient	BD	P	P	W/O(W)	R	P
Nurse	OD	T	P	W/O(W)	P(R)	P

Based on the roles in Table 3, expected functions in Table 2 and dimensions of DT in Table 1, we can assess the benefits, further needs and maturity of DT with regard to specific roles (Table 4). Finally, Table 5 provides an overview of the main areas in which the HCDT can represent an act of governance, considering societal implications [17].

Table 4. Assessment of Human-Centric Digital Twin.

Role	Benefits	Further Needs	Maturity
Operator	Reduced physical / mental workload Optimized task procedures Cooperation with machines / robots	HCDT virtual commissioning, adaptive interfaces	High
Worker	Reduced physical workload Optimized workstation	Assistive tools	Middle
Planner	Reduced mental workload Optimized data visualization	AI-driven adaptive interfaces	Middle
Decision maker	Faster information flow Better justification Better prediction	Widening/shortening of scope on demand	Middle
Policy maker	Faster information flow Better justification Faster forecast	Faster impact analysis	Low
Consumer	Additional functionality Higher product confidence	User-friendliness	Middle
Patient	Personalized treatment Higher life quality Lower risk of emergency	Lower affect by device Higher IT protection	Low
Nurse	Better monitoring of hospital Higher auditability Lower costs	Holistic view to patient Faster prediction	Middle

If you look at all these roles, then there is hardly a person left who would have been spared from working with the digital twin as digitization progressed. The particular attention will be paid to the governance supported or controlled by a digital twin (Table 5) which opens a lot of ethical issues (e.g., responsibility for false decisions).

Table 5. Human-Centric Digital Twin as an act of governance: Areas in which HCDT holds societal implications, adapted from [17].

	Five acts of governance	Processes of inclusion/ exclusion (boundary work of twinning)	Implications of boundary work
1	Steering the design of a complex system	Prioritizing some issues related to complex systems in design process and excluding others	Emphasizing and legitimizing quantifiable concerns
2	Use of data by DTs	DTs including/excluding data to be used in boundary object/digital twin	Coproducing future and existing systems and infrastructures
3	Facilitating or constraining public engagement	What kind of public concerns are digitally represented in twinning process and how they are weighted	Impacts how and whether societal actors can be involved in decision-making about complex system infrastructure
4	Opening or closing down decision-making about local constraints of complex systems	Simplification of data, e.g. reducing localization-related challenges	Co-production of infrastructure landscapes, incl. unintended consequences on landscapes
5	Legitimizing evidence for policy and management	Selecting 'objective' parts of reality to be mirrored	Potential contestation such as social opposition from prioritization of certain parts of reality and overlooking their 'political ontology'

2. Use cases of Human-Centric Digital Twin

The previously defined human roles within HCDT are described more in detail based on specific use cases.

2.1. Operator, worker, planner

This use case refers to the most common industrial scenarios when the user can interact with production systems with different roles. In particular, the user can be an operator (i.e., person who operates equipment or machines), a worker (i.e., a person who gives a job for a timeframe, usually working within a specific workstation) or a planner (i.e., a person who plans the production and the process control). They are not directly involved in the process simulation and optimization, but they are strongly affected by the design optimization actions [18]. All of them, in a different way, are part of the HCDT and their actions need to be properly replicated by the digital human-system model as presented in Figure 1. Despite their role, they can offer useful data about the executed tasks, behaviours, personal abilities, physical and mental characteristics, to be represented in the HCDT. Some data can be derived from the operator/worker/planner personal profile (e.g., age, gender, expertise, background), other data can be directly related to the task under execution (e.g., task complexity, physical and cognitive demands, duration), while further data about their individual status (e.g., cardiovascular activity, muscular activity, electro-dermic activity, eye activity) can be collected on the field from wearable or environmental sensors, and related to their level of wellbeing or stress [19].

Such a model can be used for various applications, from task validation and optimization (e.g., assembly, maintenance, quality control) to workplace design optimization, until generation of ad-hoc training programs. Systems can consist of machines, automated lines, robots, and any type of equipment used by a human being. Next, agent-based modelling can be used to simulate both the human and system actions and reactions[20]. As a result, DTs are more than just the digital representations of human-system relations, but allows to predict their mutual behaviours, to assess their interaction and to detect potential problems [19]. Virtual simulation can be carried out using digital human simulation tools, Virtual Reality or Augmented Reality [21]. The last phase of the digital loop, referring to the human-centric Virtual Commissioning, is the most challenging and not fully implemented considering human agents.

2.2. Decision maker, policy maker

A decision/policy maker is primarily interested in the process optimization through simulation, forecasting, prescription, and planning. Distinction is mostly made by a larger system and need for forecast at policy maker. For macroeconomy, for instance, a platform is needed that enable the development of macroeconomic policies in a dynamic, experimental manner as well as their simultaneous, transparent evaluation based on a real-time input. It is built using two sequential methods: economic architecture and agent-based modelling. Economic architecture investigates hidden contexts for greater transparency, and establishes the blueprint for the underlying economic model [22]. Next, agent-based modelling simulates the complex nature of the economy as it was designed or developed using this blueprint in a dynamic and realistic manner. Apart from offering trustworthy recommendations for political decision-making, the main goals of this platform are to encourage transdisciplinary research to advance our understanding of economics and to speed up the transition to an economy or society that is much more environmentally or economically sustainable and furthermore more resilient. Macroeconomists and politicians now have a suitable tool that can more accurately simulate the real economy and, as a result, offer better (objective) recommendations [23].

DTs are more than just objective representations of complex systems like the macroeconomy. In terms of effective policy decision support, DTs and land can share characteristics, encompassing physical land, virtual land, and land-related data [23]. Therefore, DTs are an outcome of the decisions made by professionals about what may and should be virtualized, as well as the sociomaterial consequences for society, infrastructure, and the environment. In this case, twinning creates "situated" knowledge about large infrastructures and their future, as well as re-creating and legitimizing expert engagement in decisions about the design, planning, and administration of such infrastructures. As such, twinning may be a form of governance in and of itself, providing reliable knowledge for decision-making [17].

A decision/policy maker works with one-directional data link builds up and uses a repository with a partial (exceptionally: identical) accuracy based on raw data of the physical part.

2.3. Consumer

The gap between the digital world, physical world and user knowledge and skills can be successfully filled by virtual and immersive reality. We need a collective human brain to fully exploit the power of the DT. More than just humans in design, we need humans with the proper tools to control the DT. Moreover, there is a need for scientific tools to conduct experiments in product/service/system design to find phenomena hidden in massive amounts of product/service/system design data and make discoveries. Different platforms (e.g., ESPACE ERCOS [24]) can be used to make it possible to explore the physical world and the digital world in continuum by using the collective human brain.

The ability to understand a person's situation holistically is improved by the exponentially rising volume of digital information and data analysis. A digital twin gives a person the capacity to portray their condition digitally in order to assist their wellbeing by using facts about them. Also, individuals can become more powerful by employing a blueprint to increase their level of self-determination regarding their personal data. This blueprint will assist public and private service and data providers in establishing a shared understanding of the function and potential of a citizen's controlled personal digital twin of themselves (a citizen digital twin, or CDT), for developing solutions that are centered on the needs of individuals. The blueprint also offers a logical structure for CDT-based service development and acts as a foundation for strategic service development recommendations [25]. This trend is enforced by various developments: personal assistants and training software, service applications for product presentation and configuration, computer games etc. Usually, a consumer works with bi-directional data link, processes data with a partial (exceptionally: identical) accuracy based on raw data of the physical part.

2.4. Patient, nurse

By advancing medical treatment with digital monitoring and human body modeling by creating a patient-specific digital model, which considers the human variability and improves individual health outcomes, DTs are progressing clinical processes and hospital administration in the healthcare [26]. The patient's imaging data, genetic information, and laboratory results can be used to create a HCDT that will help the doctor determine the best course of treatment from surgery to therapy. With progress in artificial intelligence technology, a complex system, process, or location for an early diagnosis may now be represented by a human-system digital model instead of simply a single item or component [27]. According to the framework described in Tables 1 - 3, the patient gets a role similar to a worker (on its own “physical twin”) while the nurses and doctors (i.e., hospital staff) act like operators and decision makers.

In this context, the human-system model could virtualize the entire hospital to create a risk-free setting for investigating the effects of alterations on system performance. Moreover, human employment with its dangers and consent issues is prevented by technology. When used properly, DT technology in the healthcare sector empowers doctors to select the most effective treatment, improve patient outcomes, and operate as effectively as possible, reducing hospital expenses. HCDT accomplishes this by transforming processes that traditionally required linear transactional interactions into ones that can be completed in parallel. HCDT could use sensors attached to precise objects to collect and share data about those precise objects. The goal of the DT is to create equipment in a virtual setting for design, testing, and use. Hospitals can, for instance, utilize the HCDT to automatically start sending notifications based on sensor data, rather than requiring a patient to do so. There may be a reduction in patient flow and emergency room wait times, lowering costs and improving patient satisfaction [27].

This technology can also be used to provide personalized treatments by replicating a person's genetic make-up, physiological characteristics, and lifestyle. Compared to precision medicine, which typically concentrates on larger sample sizes, it is more individualized [26]. The goal of digitizing the human body and creating precise replicas of its internal organ systems is to advance medical procedures and patient care. The use of DTs in organ modeling may provide doctors with considerable benefits, such as the detection of previously undiagnosed diseases, the testing of medications, and the improvement of surgical planning [27]. By simulating the predicted manufacturing process, a DT for medical devices enables engineers to find any process flaws before the product is put into production [28]. Engineers can control the system to bring about unforeseen events, examine how the system responds, and create mitigation plans [29].

3. Discussions and Conclusions

In this paper we discussed and defined new strategies to increase the efficiency and inventiveness of human-related processes and products using digital technologies, from industry to marketing and medicine. In the different sectors, we could define a common approach to have a human-centric digital simulation loop. In different ways, digital platforms can be used to link different sectors and industries together so that they can benefit from one another's complementary strengths. Digital innovations also give us the possibility to link existing supply and recycling networks into circular value chains.

Regarding the effectiveness, safety, risks, and sustainability of a modern product, a DT is an appropriate way for providing an architectural foundation. However, since it is so unpredictable and rarely described in such precise terms, sustainability in the human-machine interaction calls for the employment of appropriate models and approaches. Hence, in order to demonstrate sustainability in their products and services, businesses need urgent support.

In the current scenarios, the realization of HCDT has different levels of maturity according to the humans' role, as detailed in the paper. In all cases, the creation of human-system digital models is feasible in different ways using available platforms and technologies. Moreover, by utilizing system science and systems engineering approaches that are used in other industries, the creation of reliable virtual simulations is possible, integrating engineering knowledge and IT solutions. The virtual model can complement or replace specific human functions, presenting a swiftly expanding path for continued growth in this area [28]. The less exploited digital step is related to human centric virtual commissioning, which is still far away from real application. Indeed, an integrated digital application able to directly connect the physical human-system model and the virtual model for real time data visualization and control is not available yet and requires future developments. A transdisciplinary approach would stimulate the integration of technical requirements and societal requirements and can serve as the basis for continual digital system adaptation by taking into account all the pertinent aspects, including technical skills, personnel management, organization, economics, and innovation [30][31].

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