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Digital Twins About Humans - Design Objectives from Three Projects

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Digital twin (DT) emerges as a key concept of the Industry 4.0 paradigm and beyond. However, the current literature lacks focus on humans and human activities as a part of complex system DTs. Acknowledging human aspects in DTs can enhance work performance, well-being, motivation and personal development of professionals. This *study examines emerging requirements for human digital twins (HDTs) in three use cases of industry-academia collaboration on complex systems. The results draw together the overall design problem and four design objectives for HDTs. We propose to combine the machine and human-related aspects of DTs, and highlight the need for virtual-to-virtual interoperability between HDTs and machines alike. Furthermore, we outline differences between humans and machines regarding digital twinning by addressing human activities and knowledge-based behavior on systems. Design of HDTs requires understanding of individual professional characteristics, such as skills and information preferences, together with twinning between the physical and digital machine entities and interactions between the human and machine DTs. As the field moves towards including humans as a part of the DT concept, incorporating HDTs in complex systems emerges as an increasingly significant issue.*

Keywords: Digital twin, Human digital twin, Complex systems

1 INTRODUCTION

Digital twins (DT) refer usually to digital information constructs describing potential or physical products, connected with automatic transfer of data and information between the physical and the digital [1, 2]. Success stories around DTs include cases in the oil and gas [3] and aerospace [4] industries, where DTs allowed real time interaction with physical entities, coupled with future asset condition prediction. Currently, DTs have been embraced by the manufacturing industry as a driving force behind the Smart Manufacturing and Industry 4.0 paradigms [5, 6, 7]. The DT concept emerges also in such domains as smart cities and healthcare [8].

Human digital twins (HDT) have been proposed (see e.g. [9, 10]) as digital representations of individual humans. However, HDTs may also encapsulate human representation regarding processes, roles or activities without necessitating a direct mirroring of individual human beings. While the concept of DT spreads across industries and application domains, the current body of knowledge regarding DTs largely ignores humans and human activities as a part of complex systems [11]. As various application domains have noticed the potential of DTs, the question is no longer whether to integrate humans as parts of complex systems, but how to do so. Therefore, we ask: how can human DTs be realized in the future?

We discuss these needs and challenges in three industrial projects that aim at developing and utilizing DTs about humans: Human expert DT, Knowledge worker DT, and Factory worker DT. As the current DT frameworks rarely, if at all, consider humans, there is a need to formulate how HDT aspects relate to DTs. To this end, we examine HDTs from the viewpoints of field maintenance experts for large industrial machines, knowledge workers using dashboards as a part of their jobs, and factory workers in an intelligent IoT factory context. We formulate four design objectives for human aspects of DTs based on the cases. In doing so, we contribute to the DT literature by clarifying the HDT design aspects in relation to DTs of complex systems.

2 RESEARCH SETTING AND METHODOLOGY

In line with [12], we report how awareness of a design problem and design objectives emerged within three industry-academia co-innovation projects. All of the three projects identified a need for encapsulating ”digital-twin-like” elements of human workers as an important avenue for further developments. In addition to establishing this awareness of the design problem through three initial case descriptions of the respective projects, this article also proceeds to the first definition of design objectives [12, 13] and discusses their eventual novelty in relation to the state-of-the-art literature on HDTs.

We structure the design objectives by following a schema for specifying design principles for information technology-based artifacts in socio-technical systems [14]. The schema consists of four main components:

- an aim and actors as its implementers and users,
- contextual information such as boundary conditions and implementation settings,
- a mechanism that describes the acts or processes used to reach the proposed aim, and
- a rationale justifying the belief that the mechanism will achieve the aim.

For context, we situate our results within the framework of complex systems [15] – of which cyber-physical systems are an example of. Despite being intended for design principles, the schema includes goals in a specific context and the mechanisms to achieve those goals, fulfilling the requirement that design objectives should describe how a new artifact is expected to support solutions to problems not yet addressed [13].

Each project had initially and independently identified the requirement for virtually presenting humans in working roles and background research for suitable existing models or solutions had already been made. This paper unifies the project objectives to define the problem scope of HDTs in general. Table 1 presents the research projects' domain and summary of activities regarding designing the HDTs. The results form a basis for our continuing design research program [12, 13] aiming at development, demonstration, and evaluation on HDTs. While this study could be read as a three-case study per se, the jointly described novel developments in industry provide interesting implications for the subsequent efforts on HDTs for professional environments.

2.1 Human Expert Digital Twin: Oxilate Use Case

Experts of complex industrial systems often meet demands to support the emergent problems in the field maintenance and training. To address these needs, the Oxilate project develops a virtual plant (DT) concept which is a solution for DT applications for control systems connected to the customer's installed base. The project's research activities started with two researchers participating in the work package of "use case definition" together with industry partners (March – November 2020). Additionally, two interviews were conducted with industrial maintenance experts and on-going communication with developers of digital services for maintenance was established.

In the Oxilate DT system, metadata, real-time data and 3D models will be combined to realistically represent the plant and its control flows in operation. The field worker will interact with the virtual plant through a virtual HDT "expert" which provides relevant information for the worker based on information-inquiring interaction. Increasingly, the virtual expert will provide automatically observed context in which the worker is interacting with the physical reality of the machine(s) to be serviced. The intelligent support through HDT is expected to enhance the fieldwork and training reducing the need for the busiest experts to interact onsite.

The virtual expert must be modeled in a way that includes smooth human interaction, information seeking behavior connected to a work context (e.g. maintenance), decision-making and tacit expert knowledge. So far, DTs in the Industry 4.0 context have been used mainly to represent the physical components of the system (e.g. industrial process) but this use case extends the DT with expert human behavior interacting with the physical system and its HDT that cannot be pre-determined fully. The first step is to provide a mechanism in a virtual plant to present relevant information of some problem for human decision-making and actions, which must be augmented by digitized information and knowledge with a knowledge graph.

2.2 Knowledge Worker Digital Twin: VISDOM Use Case

Modern software development processes, such as DevOps, requires collaboration between different stakeholders within organizations. As such processes produce an ever-increasing volume of data, utilizing it and establishing high-level views of the development process for varying stakeholders remains challenging. Visualization provides an accessible way of gaining an overall view of the development process and enables effective detection of process anomalies based on visual patterns. However, most existing visualization tools are bound to specific data sources and are presented from a single point of view. The VISDOM project aims towards constructing dashboards for software development processes with stakeholder specific visualizations.

The Knowledge Worker HDT was proposed as it enables more explicit representation of the user's information and knowledge needs for decision making. Additionally, the HDT provides relevant information to support human decision-making process in both role and task specific contexts and acts as a representative in automatic decision-making processes regarding the presentation of information. The project did not aim at HDT from the start but rather the need was discovered as a part of conceptualization activities. The need for designing the human DT was discovered after four researchers organized and conducted two focus groups with three industry partners and several interviews with individual company representatives (September 2019 – March 2020).

Development of the Knowledge Worker HDT would allow for a more explicit way of representing and gaining visibility on worker's information and knowledge needs based on their task, role and organizational background. The HDT is expected to select default individualized contents for each dashboard view and, over time, learn how the dashboard is used, which information or knowledge is used for specific task and by whom. These analytics would be used to improve available visualization and the HDT's selection accuracy over time through machine learning or other suitable means. Furthermore, the Knowledge Worker HDT may also flag information needs as unfulfilled if certain visualizations are missing from the dashboard. By doing so, the HDT facilitates communication and transfer of information and knowledge between persons.

2.3 Factory Worker Digital Twin: Reboot IoT Factory Use Case

Along with the rapid digitalization of the manufacturing industry, novel solutions for AI assisted production

Table 1. Summary of relevant attributes for a common HDT solution between cases

Design objectives	Oxilate	VISDOM	Reboot IoT Factory
Human representation (DO1)	Information for decision-making and tacit expert knowledge of work tasks	Role and task specific information and knowledge needs for decision making	Worker competence, education, experience, preferences, limitations, availability
Human twinning (DO2)	Monitor worker information seeking and actions	Monitor worker information seeking	Input from worker and sensing equipment
Expert knowledge and the behavior associated with it (DO3)	Relevant and contextualized maintenance information based on information-inquiring interaction	Contextualized information or knowledge for tasks and roles based on usage	Skill and wellbeing development, task related feedback and real-time information from the factory floor
Digital and physical interactivity (DO4)	Field worker interacts with virtual plant through HDT, HDT provides information to worker	HDT provides information for knowledge worker	AI-Foreman interacts with worker HDTs, HDT assists in work planning and well-being coaching

planning and management are needed. The introduction of IoT and AI in the manufacturing process demands handling data of the production environment more than ever before. The nature of the factory work is changing along increasing automation. Availability of production data, DTs of the production lines and the products have opened the potential to optimize production in real-time. Including the worker resource allocation to optimized real-time production planning requires novel solutions for factory foremen. Dynamic model of the foremen's work was conceptualized in Reboot IoT Factory project; an AI-powered advanced planning and scheduling (APS) assistant for the human foreman: AI Foreman[1].

Two group interviews with six foremen & production planners (May 2020), and a two-day workshop with 27 participants (June 2020) were held to define the need and purpose for Worker DT. Preliminary literature search was conducted on work planning, allocations and worker role in them. The need for modeling the worker and human aspects were recognized during AI Foreman conceptualization. Planning production and work allocation demanded human involvement from the foremen that takes time and complicates performing fast changes in the production.

Due to the changing work environment, systematic information of the work and the worker could be used to create meaningful, and fair work and to promote personal well-being at work. The personal skills and preferences should be based on the information that the worker is willing to give and able to modify. The designed Factory Worker HDT acts as an enabling concept for better optimization of the production, and for gaining visibility to employee's personal skills and preferences regarding the work tasks or working hours. Worker HDT include components related to employee information, such as competence, education, experience and availability to tasks at work, and task related data, such as cognitive or physical load of the task. One important impact of the Factory Worker HDT is the ability to update it in real-time to provide up-to-date information about the status of the manufacturing process. In practice, this means that the HDTs of workers and HDTs of foremen or production lines have to be connected. Finally, the HDT should be able to provide feedback and hints for the worker how to increase wellbeing and recovery during their free time. Ethical and privacy aspects must be carefully considered in HDT design and development, as well as high regulation related to collecting information from workers.

3 ANALYSIS AND RESULTS

In this section, we present design objectives based on the industry-academia projects that establish the need to model humans in connection with the industrial systems. Based on the commonalities between cases (Table 1), we propose shared design objectives (DO) for a possible solution to guide future HDT implementations. As the cases have not yet been realized in practice, we define what should be modeled in HDTs (DO1), how twinning can be achieved with HDTs (DO2), how HDTs can

[1] https://rebootiotfactory.fi/rebootiotfactory/future-work-with-ai-foreman-in-digital-factory/

support and learn from experts in the field (DO3), and how HDTs interact with humans and their surroundings (DO4). Each of the commonalities between cases is introduced in the following sections. The design objectives are summarized in Table 2 with further research opportunities based on each presented design objective.

3.1 Human Representation (DO1)

The Human Expert, Knowledge Worker and Factory Worker HDTs evolve to digital representations of real workers. As workplaces rapidly digitize and automate, a shared need has emerged for a more in-depth understanding of the workers themselves and of the tasks they perform in relation to their working environment. HDTs allow for a more rigorous way of understanding the needs, capabilities and limitations of human workers as a part of workplace processes. Furthermore, HDTs make it possible to determine how various human aspects affect work-related tasks and how these tasks in turn impact both physical and mental well-being.

Creating digital representations of humans begins by understanding who they are and what they do. The Factory Worker HDT, for example, represents human skills, preferences, limitations, availability and other factors that are not directly measurable. The Human Expert and Knowledge Worker HDTs on the other hand relate more towards modeling human knowledge and the expert behavior associated with it. Regarding to what humans do, the Human Expert, Knowledge Worker and Factory Worker HDTs all feature modeling the worker's tasks and context as a core aspect of their functionalities. In each case, the understanding and transparency of workforce and the tasks they perform grows as HDTs capture aspects of worker personalities and behavior.

Digitally representing aspects of humans and their activities as parts of complex systems allows us to extract the design objective of **human representation**: *For designers and engineers (implementers) to better understand worker activities and expert knowledge, and thus support workers in their knowledge-based tasks (aim) within organizations (users) as parts of complex systems (context) by representing unquantifiable human attributes and accumulating expert knowledge as a part of HDT design (mechanism) because doing so allows for a more rigorous way of understanding the needs, capabilities and limitations of human workers as a part of workplace processes (rationale).*

3.2 Human Twinning (DO2)

Identifying and quantifying human-related information, needs and task completion is based on monitoring and measurements. As per definition, the flows of information and data between DTs and their physical counterparts, their physical-to-virtual and virtual-to-physical twinning connections, are both bidirectional and automatic. Automatically exchanging information between digital entities and machines requires well-defined interfaces, where both entities know exactly how communication is conducted between them. Human entities introduce an aspect of uncertainty through decision-making and acting in the physical world. Unless a human consciously communicates to its HDT, the automatic flow of information is dependent on either directly measuring the human or on gauging the impact of their actions on the physical world.

Detecting and propagating state changes for HDTs can be challenging due to difficulties of measuring humans and the changes they realize on the physical world. Directly quantifying or measuring workers and their actions may be more feasible in the Factory Worker case than the Knowledge Worker or Human Expert cases as expert-based tasks are harder to quantify than physical labor. Additionally, the context of work affects the amenability of using sensors and IoT devices for direct measurements instead of only utilizing data from digital interaction. The selected measurements and data collection methods heavily influence twinning rate and can possibly lower it between HDTs and their human counterparts when compared to DTs related to machinery. Machine-related measurements tend to better map to attributes that can be directly measured from the physical world with sensors, whereas abstract measurements such as well-being, satisfaction, mood, motivation and stress tend to be indirect and may require asynchronous data collection methods such as surveys.

Thus, we extract the design objective of **human twinning**: *For designers and engineers (implementers) to facilitate the twinning process of humans (aim) within organizations (users) as parts of complex systems (context) by supporting both direct and indirect measurements alongside synchronous and asynchronous transfer of data (mechanism) due to the complexity of capturing the states and behaviors of humans and the availability and acceptability of sensing equipment as part of work (rationale).*

3.3 Expert Knowledge and the Behavior Associated with It (DO3)

The HDTs of these projects were envisioned to affect the way humans work and support information-seeking and decision-making activities. The Factory Worker HDT helps maintain well-being by reminding its human counterpart about breaks while working and provides hints for

Table 2. Design objectives based on three industry-academia projects with further research opportunities presented by each design objective. The design objectives are mapped to the HDT concept in Fig. 1.

Design objectives	Research opportunities
Human representation (DO1)	– *How can human aspects, and behavior linked to them, be digitally represented to form a contextually meaningful virtual entity?* – *How could digital twins of humans be used to better understand workers and the tasks they perform in relation to their working environment?*
Human twinning (DO2)	– *To what degree are the flows of data between humans and digital twins both bidirectional and automatic?* – *How to facilitate both direct and indirect measurements alongside synchronous and asynchronous transfer of data between humans and digital twins?* – *How to address the challenges of including humans in digital twinning?*
Expert knowledge and the behavior associated with it (DO3)	– *How could digital twins be used to augment information-seeking and decision-making activities?* – *How could digital twins be used to accumulate, digitally represent and communicate expert knowledge and the expert behavior associated with it as a part of workplace processes?* – *How could digital twins be used to develop an individual's skills and well-being over time?*
Digital and physical interactivity (DO4)	– *How could HDTs be used to exchange information without human intervention?* – *How to facilitate virtual-to-virtual interoperability between digital entities and external digital systems?* – *In which ways could humans and digital twins interact and exchange information?*

boosting recovery on their free time. Furthermore, the Factory Worker HDT provides task related feedback and real-time information from the factory floor. The Knowledge Worker HDT provides relevant visualizations based on interests, roles and tasks, while the Human Expert HDT provides knowledge-based guidance in maintenance tasks.

Each case description featured learning about humans and their way of working. Both the Human Expert HDT and Knowledge Worker HDT feature learning about information and knowledge humans utilize in specific tasks and scenarios. The Human Expert HDT must be able to accumulate, digitally represent and communicate expert knowledge by learning how humans search for specific information and how they behave in doing so. The Knowledge Worker HDT operates in a similar fashion by studying information sought for in specific cases and roles. The Factory Worker HDT, on the other hand, focuses more on how employee skills and well-being develop over time. However, each case utilizes these results in helping humans, also including others than the twinned ones, to carry out their tasks more effectively in each context.

Affecting the way of working along supporting information-seeking and learning from expert tasks with HDTs allows us to extract the design objective of **expert knowledge and the behavior associated with it**: *For designers and engineers (implementers) to affect the way humans work along augmenting information seeking and knowledge-based behavior (aim) within organizations (users) as parts of complex systems (context) by accumulating information and knowledge from worker activities (mechanism) because doing so allows for the learning and distribution of expert knowledge and behavior (rationale).*

3.4 Digital and Physical Interactivity (DO4)

In each of the presented cases, the worker HDTs interact with external digital systems and act as intermediaries when information is processed either automatically or outside of the employee's working hours. Both the Human Expert and Factory Worker HDTs exchange information without human intervention, the former within a vir-

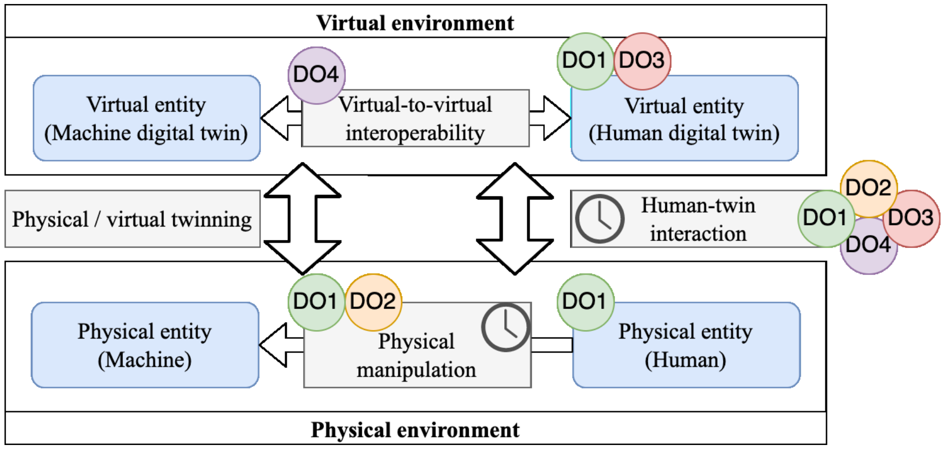

Fig. 1. The different connections of machine and human digital twins. Each arrow represents a connection, described with gray boxes, between entities marked with blue boxes. The clock symbols represent human induced latency or stochasticity. The colored circles represent the proposed design objectives, positioned to reflect their placement within the HDT concept.

tual factory and the latter by interacting with the AI Foreman. Both the Knowledge Worker and Factory Worker HDTs communicate their physical counterpart's preferences in work related matters, while the Human Expert HDT goes even further by independently providing help to other humans attempting similar maintenance operations. To this end, each worker HDT augments or emulates knowledge-based human behavior.

Connecting virtual entities allows them to share data and respond to changes in virtual environments in real-time. When combined with other digital "things" in a shared digital environment, virtual-to-virtual interoperability (Fig. 1) becomes essential in simulating larger virtual entities such as whole factories. Simulation and the real-time exchange of data allows for gauging the impact of tasks on workers and the impact of human behavior and well-being on workplace processes. However, when HDTs communicate to their physical counterparts, they affect physical reality through the information they provide for decision making. In doing so, they are reliant on humans interpreting, understanding and acting on the provided information. Interpretation is a subjective process that is always different due to the unique viewpoints represented by each interpreter. Furthermore, interpretation in virtual-to-physical interaction with HDTs introduces an element of stochasticity while machinery related DTs can affect physical reality in a more deterministic way by directly manipulating the physical object they are twinned from.

Enabling connectivity and interaction between humans, DTs and other systems leads us to the design objective of **digital and physical interactivity**: *For designers and engineers (implementers) to enable and facilitate digital and physical interaction between humans, digital twins and external systems (aim) within organizations (users) as parts of complex systems (context) by allowing digital twins to act on behalf of humans in automated processes and to provide useful information and feedback for decision-making (mechanism) because doing so allows for lessening the burden of workers and further immersing the personal aspects as parts of automatized processes (rationale).*

4 DISCUSSION AND CONCLUSIONS

Above, we report how a design problem of HDT arose from new industry developments within three industry-academia projects. The three on-going projects illustrate the need for understanding humans in the context of workplace processes with emphasis on interaction between humans and digital entities. Our use cases with the Human Expert, Knowledge Worker and Factory Worker HDTs each illustrate the need for representing elements and behavior of human workers beyond plain numerical representations. To answer the question of how HDTs can be realized in the future, we propose four design objectives (Table 2) for a larger design science research program based on the presented problem definition.

While previous works have primarily focused on twinning cyber-physical systems and machines, such as factories and production lines within the manufacturing domain, we focus on the HDT aspects of the worker – advancing the research issue of humans in Digital Twin applications [11]. It should be noted that our use of the concept differs from previous HDT approaches (see e.g.

[9, 10]) that focus on directly mirroring real individuals in the physical world. Our approach considers HDT as *an abstraction of workers that encapsulates human aspects or involvement in a digital twin compatible format*, which may cover representations of roles, specific types of characters or human-related activities for simulation purposes.

While the majority of DT literature considers the connection between physical entities and virtual entities [11, 16, 17], a fully conceptualized approach to HDTs does not exist as of writing this article. However, our results align with several previous works that address the concept from different angles. Our design objectives regarding worker representation are in line with contemporary worker model concepts that target an increasingly wider selection of personal information and capabilities of workers – such as workload and task history data, collected to determine, for example, the fatigue level of workers (see [18, 19, 20]) – along with human aspects such as individual skills, ergonomics, and even personalities [21]. Digitalization of worker experience and expertise can be found from emerging industrial research focused on capturing implicit knowledge of task execution (see [22, 23, 24]).

HDTs can be based on or utilize measurements originating from humans, such as the athlete's HDT [25, 26], human cardiovascular system [25, 27], and healthcare processes [28] and services [29], but these approaches capture few aspects of humans to allow increased impact and transparency of work along with learning from expert knowledge and behavior on an organizational level. By modeling aspects of human knowledge, and the knowledge-based behavior, HDTs may be a key in simulating processes or systems that include inherent asynchrony and stochasticity due to human activities. We consider that the closest reference points of HDTs in previous works lie on integrating HDTs in production control [24] and on the Operator 4.0 interface [19].

While we point out out objectives for the new design aspects observed in three cases, the detailed solutions for HDTs remain under development. Combined with the observed lack of academic discussion on HDTs, the findings of this paper will be further elaborated in subsequent design research effort while learning continuously from other settings as well. As the research literature around DTs matures, the field is slowly converging towards the inclusion of human aspects in digital representation and simulation activities. We contribute to this development with the introduction of differences of humans and machines regarding digital twinning, the need for modeling human knowledge, virtual-to-virtual interoperability within the concept itself, and research opportunities. The suggested design objectives can be utilized by both practitioners and researchers, highlighting aspects of communication with DTs, HDTs, and the entities of the physical world.

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