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# A Systemic Human Digital Twin Model for Human-Centric Systems<sup>\*</sup>

Ben Gaffinet<sup>\*,\*\*</sup> Yannick Naudet<sup>\*</sup> Hervé Panetto<sup>\*\*</sup>

<sup>\*</sup> *Luxembourg Institute of Science and Technology, Esch-sur-Alzette, L-4022, Luxembourg*

<sup>\*\*</sup> *University of Lorraine, CNRS, CRAN, Nancy, F-54000, France*

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## Abstract:

Human Digital Twins (HDT) are a key technology to enable human-centric manufacturing systems. This paper presents a novel meta-model for HDTs, grounded in general systems theory, to provide a unified and robust conceptualisation for HDT development. The model describes four essential interacting systems categorised by the physical or digital nature of their components; (i) the *Human Individual* is a physical system composed of a physiological, cognitive and mechanical sub-system among others; (ii) the *Human Digital Twin* is a digital system composed of a human model, data storage and management capabilities, and functions to generate feedback for the human; (iii) *Sensors* are cyber-physical systems capturing observations about the human and digitising them for the HDT; (iv) *Human-Machine Interaction Devices* are cyber-physical systems enabling the human to receive feedback from the HDT and interact with it. The systemic grounding provides a general model of an HDT as an extension of a DT representing any kind of system. It clarifies the relations and interfaces between its four main sub-systems, as well as the data flows and feedback mechanism. The HDT's *Communication Interface* is identified as key component to integrate HDTs into larger digital ecosystems and enable human-centric system development.

*Keywords:* Human-Automation Integration; Smart manufacturing systems; Industry 4.0, Human Digital Twin, Industry 5.0

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## 1. INTRODUCTION

Industry 5.0 pushes for the development of sustainable, resilient, and human-centric manufacturing systems (Breque et al., 2021). Human-centricity puts the human worker at the centre to enhance their capabilities through a symbiotic human-machine relationship. Machines should adapt to the needs and preferences of the human, and this requires a good awareness of the human state (Lu et al., 2022). This includes the physiological, psychological, and cognitive state, but measuring these is a challenging endeavour and necessarily involves gathering sensible personal information about the human. With the rise of Digital Twins as key pillars of modern factories, the Human Digital Twin (HDT) emerges as a promising tool to support human-centricity. An HDT is a digital representation of a human individual that emulates their state and behaviour (Gaffinet et al., 2025). It centralises the data about the human and selectively shares relevant information with surrounding systems. HDTs may host models of human cognition, psychology, or personal preferences to enable the sought-after awareness of the human state. A well-designed HDT can gather personal data, emulate the human, and enable human-centric systems without compromising privacy.

HDTs first appeared in 2017 and spread to an increasing number of application domains. This led to a multitude of conceptual interpretations, but the main components are the human individual, or physical twin; the HDT itself; and devices that enable the dataflow between the two. Various models seek to clarify the relationship between these elements, but there is still no consensus, in particular, in the place of data sources and feedback mechanisms. He et al. (2024) propose a framework placing the data sources within the Physical Twin and feedback interfaces within the Virtual Twin. In contrast, Lin et al. (2024) consider feedback interfaces as separate from the HDT, but assign data sources to the human. Lauer-Schmaltz et al. (2024) explicitly integrate feedback interfaces into the HDT and present a vision of embodied HDTs. Miller and Spatz (2022) introduce a single interchange component for all data flows between the physical and digital world, providing no clear distinction. Layer-based architectures tend to not specify whether data collection and feedback mechanisms belong to the HDT (Wang et al., 2024; Shengli, 2021). Beyond the need for conceptual clarification, most HDT models focus on isolated representations of individuals, disregarding their integration into a larger digital ecosystem. In contrast, high-level layer-based architectures include the larger ecosystem but provide little guidance on how to separate the various physical and digital entities to manage their interactions.

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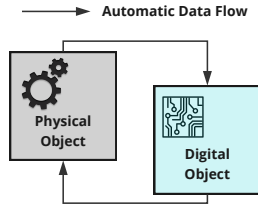


Fig. 1. Digital Twin data flows as described in Kritzinger et al. (2018)

To address these shortcomings, this paper presents a meta-model grounded in General Systems Theory (GST). With GST it is possible to create a generic and unified model while at the same time anchoring the model in clearly defined concepts and principles. Here, we build on the preliminary model defined in Naudet et al. (2023), focussing on the HDT. In addition to identifying the main systems involved in HDT development, we clarify the role and position of data sources and feedback mechanisms. An analysis of each system is provided in terms of their relations, structure, components, interfaces, and environment. This includes the required interfaces to enable the integration of HDTs into a larger digital environment or ecosystem. The ultimate objective of our model is to lay the groundwork for a standardised and integrated approach to HDT development.

## 2. DIGITAL TWINS FOR HUMANS

A Digital Twin (DT) is “a set of adaptive models that emulate the behaviour of a physical system in a virtual system [...]” (Semeraro et al., 2021). Its primary objective is to emulate the twinned physical system in order to “predict failures and opportunities for changing, to prescribe real time actions for optimizing and/or mitigating unexpected events” (Semeraro et al., 2021). A second important aspect is the data flows between the DT and the physical system, as illustrated in Figure 1 following the view of Kritzinger et al. (2018), who moreover distinguishes between *Digital Models*, *Digital Shadows* and *Digital Twins* based on the level of data integration. A DT is then a *Digital Object* connected to a *Physical Object* (the twinned system) through an automated bi-directional data link allowing emulation and feedback. Kritzinger et al. (2018) express it concisely as “A change in state of the physical object directly leads to a change in state of the digital object and vice versa”.

Human Digital Twins are a special case of DTs where twinned physical systems are humans. In prior work, we discussed the differences with traditional DTs and provided a general definition for HDT: “*Human Digital Twin is a class of Digital Twin whose twinned entity is a human individual. It is a digital representation of the twinned human, emulating their state and dynamics. It automatically receives data, with optional manual entries, and provides automatic feedback directly to the twinned human.*”. (Gaffinet et al., 2025)

As the model we develop should be coherent with the given definition, a first necessary condition for an HDT is that its twinned entity is a human individual. Traditional DTs can have any physical system as their twinned entity, whereas

for HDTs, it is necessarily a human. This comes with a wide variety of specific challenges, such as gathering data from humans, especially when information about cognitive processes (Lauer-Schmaltz et al., 2022) is needed.

The objective of the HDT is very similar to that of traditional DTs, as both seek to emulate their twinned entity. Although creating traditional DTs is in no way trivial, the complexity of a human exceeds that of technical systems. Modelling the numerous physiological, cognitive, and mechanical processes and their dependencies is a major roadblock for holistic HDT development. The previously mentioned personal nature of the data makes data security and privacy a duty of the HDT. Explainable and reliable models are an important requirement to avoid negative outcomes for the twinned human and build trust in the HDT.

Like any DT, a HDT needs suitable interfaces to implement the bi-directional dataflow with the twinned human. Those interfaces could be part of a DT; however, if we consider it as a pure digital system, they should not. In the case of the HDT, we have two additional elements involved in the DT-Physical Twin communication flow: *Sensors* and *Human-Machine Interaction (HMI) Devices*, that both serve as a bridge between the physical and digital world. *Sensors* gather data about the twinned human automatically and send them to the HDT. *HMI Devices* enable interactions between the human and their HDT. Feedback from the HDT, as well as manual input from the human, is mediated through this component. It may take the form of a tablet or screen and can loosely be referred to as the human-machine interface.

From the general definition emerge four essential elements to create an HDT, namely (1) *Human Individual*; (2) *Sensors*; (3) *HMI Devices*; and (4) the *Human Digital Twin* itself that is deeply dependent on the three other elements. Figure 2 illustrates these elements including their relations. The *Human Digital Twin* emulates the twinned *Human Individual*. One or multiple *Sensors* observe the *Human Individual*, produce data about them and send it to the *Human Digital Twin* enabling the required automatic data collection. The *HMI Devices* enable automatic feedback and additional manual input that the human may wish to provide.

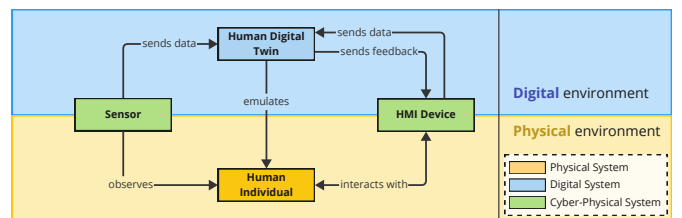


Fig. 2. The *Human Digital Twin - Human Individual* pair, and the essential elements to enable emulation of the human by the HDT and interaction between both.

Figure 2 illustrates the digital and physical environment using a coloured area. The four main elements are colour coded and categorised as *Digital*, *Physical* and *Cyber-Physical Systems* respectively. In the next Section, we introduce the systemic approach and the rationale for these categories.

### 3. SYSTEMIC GROUNDING

Von Bertalanffy (1972) introduced General Systems Theory (GST) which originated in the field of biology in an attempt to address the complexities of biological organisms. Despite its origin, the theory defines core principles and concepts that are applicable to any domain. Since then, the theory has found success in numerous domains, including engineering and ecology. As a general theory, it goes back to the fundamentals of the complex objects that make our environment, their structure, and their dynamics, including not only biological systems like humans but also engineered systems like cyber-physical systems and digital twins. For this reason, it provides a strong ground for building a generic model for digital twins, and in particular HDT.

Figure 3 illustrates the components we retain as a basis for a system in its environment and a categorisation of the systems involved in HDT development. A *System* is defined by its components which interact with each other forming a coherent whole in an environment in which it acts. These components may be systems themselves. At its boundaries, it interacts with its *Environment* through *Interfaces*. The environment is itself a system, like the interfaces. Additionally a *System* has *Objectives* and *Functions* to realise them. (Le Moigne, 1990). Throughout the paper, we use the same three colours as a shorthand for *Digital Systems* (blue), *Physical Systems* (yellow) and *Cyber-Physical Systems* (green), while all other elements are shown in a default grey colour.

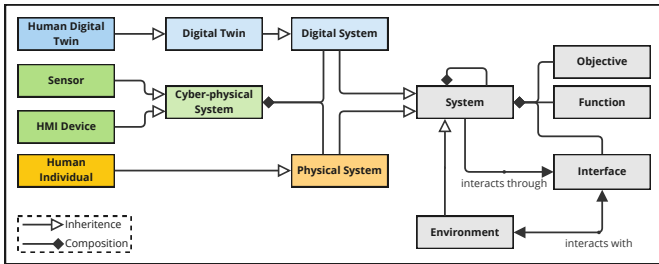


Fig. 3. The four essential elements for HDT development as different types of systems, and the main elements of a systemic model.

Each of the HDT's essential elements can be conceptualised as a system, with its own internal dynamics, interfaces, functions, and objectives. An HDT is defined as a digital representation and exists exclusively in the digital world. For conceptual clarity, we define *Digital System* as a *System* that consists exclusively of digital components. Both traditional DTs and HDTs are *Digital Systems* following this definition. Analogously, a *Physical System* consists exclusively of physical components, making the twinned human individual a purely *Physical System*. The two remaining systems, *Sensors* and *HMI Devices*, have the role of transforming physical signals into digital signals and vice versa. Bridging the digital and physical world can be considered as their objective. To achieve this, they must be able to simultaneously interface with *Physical Systems* (*Human Individuals*) and *Digital Systems* (*Human Digital Twins*). Hence, they necessarily have physical and digital components at the same time. This type of system is referred to as *Cyber-Physical System* (CPS) (see

Lezoche and Panetto (2020) for a meta-model). A CPS is composed of a physical component and a cyber component, characterised by a high level of integration. In the context of this paper, cyber components and digital components are treated as synonymous.

### 4. HUMAN DIGITAL TWIN MODEL

This Section presents the HDT as a *Digital System* by describing its digital components, interfaces, objective, and functions. The objective of an HDT is to emulate the twinned human and provide feedback to support them. Three digital modules are needed to achieve this objective. A *Data Storage and Management* module pre-processes and stores the received data. It has the role of structuring and protecting the data appropriately. A *Human Model* exploits the data to reflect the status and behaviour of the twinned human. Lastly, *Human Digital Twin Functions* may use both the data and the human model to generate the desired feedback for the twinned human. The components are described in detail later.

The boundary of the HDT is materialised by its interfaces, which facilitate data exchange with external systems and the environment. A first interface is the *Data Acquisition Interface* whose role is to connect data sources about the twinned individual to the HDT. It can only receive digital signals; therefore, the sensors need to transform the detected physical signals into digital signals before transmitting them. The *Data Acquisition Interface* is mandatory to enable the necessary automatic data gathering for the HDT. Feedback to the human is managed by a *Feedback Interface*.

Lastly, a *Communication Interface* has the task of connecting the HDT with other DTs or technical systems, which can be considered the digital environment of the HDT. It is a key component to enable adaptive systems and enriching the HDT with contextual data. Through it, contextual information about the environment can be fed into the HDT and exploited for context-aware models. At the same time, it allows the HDT to send information to other technical systems for adaptation. The *Communication Interface* is a necessary component to integrate an HDT with a larger digital ecosystem, such as a smart factory.

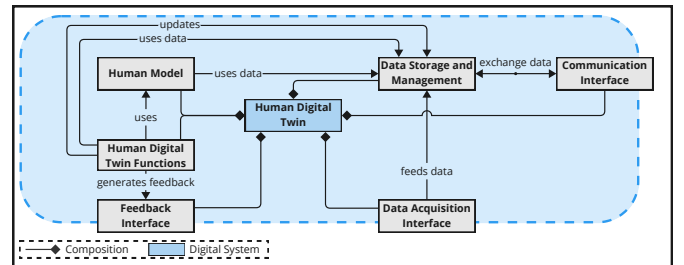


Fig. 4. Model for Human Digital Twin.

Figure 4 illustrates the HDT as a *Digital System* indicated by the blue box. The interfaces are depicted on its boundary to indicate their role as a bridge between the HDT's internal components and the environment. When data is received through the *Data Acquisition Interface*, they are sent to the *Data Storage and Management* module. This module cleans and pre-processes the data before storing

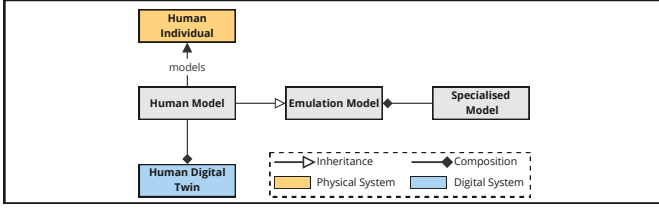


Fig. 5. Human model: the Emulation Model of the Human Individual, as a composition of specialised models of the HDT’s twinned entity.

it for further use. It may receive additional data on the environment through the *Communication Interface*. Organising data from heterogeneous sources and fusing the data appropriately is a considerable challenge (Pesapane et al., 2022). For real-time applications, data streams may also be set up. At the level of the the *Data Storage and Management* module, access policies and privileges are managed, thus enabling the protection of personal data and privacy. What kind of data are available for sharing needs to be decided here.

The *Human Model* is at the core of the HDT in its role of emulating the twinned human. A successful human model produces the same output as the real system for a given input. It uses data from the *Data Storage and Management* module to update itself and reflect the state and behaviour of the human. The human model may be composed of multiple specialised models, each addressing a different aspect of the human while being interlinked with one another. In practice, the scope of the model is restricted to a few aspects, as the full complexity of the human exceeds current modelling abilities. The model outputs are a potential input for the *Human Digital Twin Functions*.

*Human Digital Twin Functions* can take various forms with the goal of generating feedback to support the human. They may use the data and models of the HDT and can run automatically or be triggered on demand by the human. A noteworthy example is the simulation function for which the model is run with hypothetical input data to analyse the behaviour of the human under those circumstances. To run such a simulation, the circumstances and their evolution need to be modelled as well. HDTs can also be used to predict the state of a human in the near future by running the human model for multiple time steps. This may be used to avoid dangerous situations by sending preemptive warnings. The manually triggered function may include data analysis. For instance, an athlete may query their HDT’s analytics function to visualise the trend of their fitness.

## 5. HUMAN MODEL

A specific challenge for HDTs is modelling the twinned human and his behaviour for emulation purposes. For a traditional DT, the emulation model is typically composed of multiple specialised models covering the various aspects of the twinned physical system, which are not represented in figure 4. For an HDT, the emulation model interlinks models about human aspects such as physiological and cognitive models. Figure 5 zooms in on the emulation model in the case of HDTs, where it refers to the aggre-

gated emulation model for the human individual, named *Human Model*. In this Section, we present a meta-model for humans that outlines and organises the main components needed to emulate human behaviour and actions.

We conceptualise the *Human Individual* as a *Physical System* that consists of a set of components or sub-systems, and a boundary to separate it from the environment. The boundary would include the physical body of the human, which is best delineated by the skin. All internal organs, muscles, nerve strains, etc., are components of the human body and give rise to a large variety of processes, including biomechanical and cognitive processes. Properly defining the interfaces with the environment is challenging and depends on the modelling scope and perspective. For example, a diet model may consider the mouth and excretory system as interfaces, while a cognitive model would consider sensory and motor organs as the main interface with the environment.

We consider that the human can be divided into a set of sub-systems, enabling a more focused modelling approach. In Figure 6, we illustrate the division into *Physiological*, *Mechanical* and *Cognitive* sub-system with a detailed view on the *Cognitive System*. Our human model is composed of the three systems, but additional systems may exist. Each of the systems may be further divided, for example, the *Physiological System* may be subdivided into a cardiovascular, respiratory, and immune system. Each sub-system has attributes, but the interplay between multiple sub-systems may lead to the emergence of additional global attributes. For example, both the cognitive and physiological systems may impact the psychological attributes of a human.

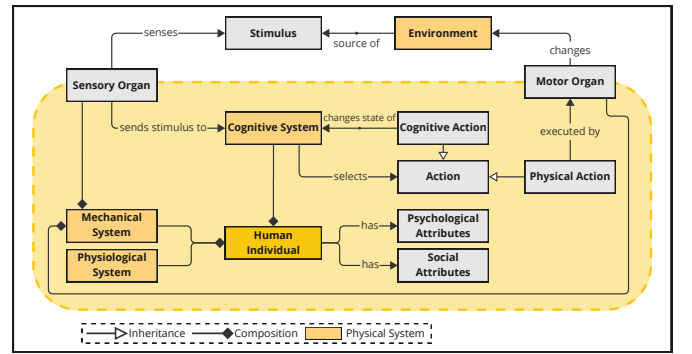


Fig. 6. Model of a *Human Individual* as a *Physical System*, including the main sub-systems and interaction with the *Environment*.

Figure 6 gives a closer look at the interactions between the *Human Individual* and *Environment* take place. It involves two major systems; the *Mechanical System* to perceive the stimuli from the *Environment* and execute *Physical Actions*; and the *Cognitive System* to process stimuli and select what actions to perform. Here, the interfaces with the physical world are the *Sensory Organs* and *Motor Organs* which both belong to the *Mechanical System* of the human. The environment is the source of a stimulus that is sensed by the sensory organs. Subsequently, the cognitive system processes this stimulus to select an action and create a motor plan. Through the execution of the action, the environment changes, generating a shift in the

sensed stimuli or a new one. A human may also take a *Cognitive Action* as a reaction to a stimulus that leads to a state change in the *Cognitive System*. An example is a human mentally replanning how to perform a task after noticing faulty equipment.

Modelling human cognition is a major challenge, but a promising cognitive modelling approach comes from the cognitive sciences. These models are known as cognitive architectures and seek to model human cognition based on the assumption that the human brain works as an information processor. Their structure is informed by neurology insights about the brain regions and their functions. Many architectures exist, but follow a similar structure. The common elements have been synthesised by Laird et al. (2017) in an attempt to create a “*Standard Model of the Mind*”. The main steps of the cognitive process are the following. Once a stimulus is sensed, the information is filtered and interpreted; this process is often unconscious but can be elevated to require conscious attention. The processed stimulus enters working memory, which may trigger the retrieval of long-term declarative and procedural memory. Long-term memories contain knowledge and procedures learnt in the past and contribute to the selection of an action and the development of a motor plan. Once a motor plan is executed, it leads to a change in state in the environment. From the execution of actions and the observation of its effects, humans learn to adapt their approach, which can be represented by new memories that are formed and stored in long-term memory for future use.

## 6. SENSORS & HMI DEVICES

In this Section, we describe two systems required to establish automatic bi-directional communication between the HDT and the Human Individual, namely *Sensors* and an *HMI Devices*, and discuss the data flows they enable. Finally, we consolidate all the systems discussed thus far into a holistic systemic meta-model.

*Sensors* are composed of physical components to detect physical signals, as well as digital components to store, transmit, and potentially pre-process the physical information. The exact boundary between the two is debatable, but for this paper we define the boundary at the conversion from a physical to a digital signal, or vice-versa. An example of this is a microphone. It is composed of physical components (membrane, amplifier, housing, analogue-to-digital converter) and digital components (signal processor, transfer protocol) with the analogue-to-digital converter at the boundary.

The *Sensors* observe physical phenomena originating from physical systems, including the human individual and its environment, and transmit the information to the HDT. Observing a human includes observing their actions and the effect on the environment. From the state and evolution of the environment, it is possible to capture information about the stimulus that the human receives.

The *HMI Devices* have two roles: transforming digital signals from the HDT into human-understandable physical signals and transforming manual physical entries by the human into digital signals for the HDT. Like for *Sensors*,

it has both physical and digital components to interface with the human and HDT. It enables automatic feedback to be sent to the human. As an example, the HDT may suggest to the human to take a break, by sending a digital message to the *HMI Devices* that is translated into a text message on a screen. In this example, the screen is a physical component of the *HMI Device* while the digital processes to receive and transform the HDT’s message are digital components. Inversely, a physical signal, such as a keystroke, can be translated into a digital signal and sent to the HDT.

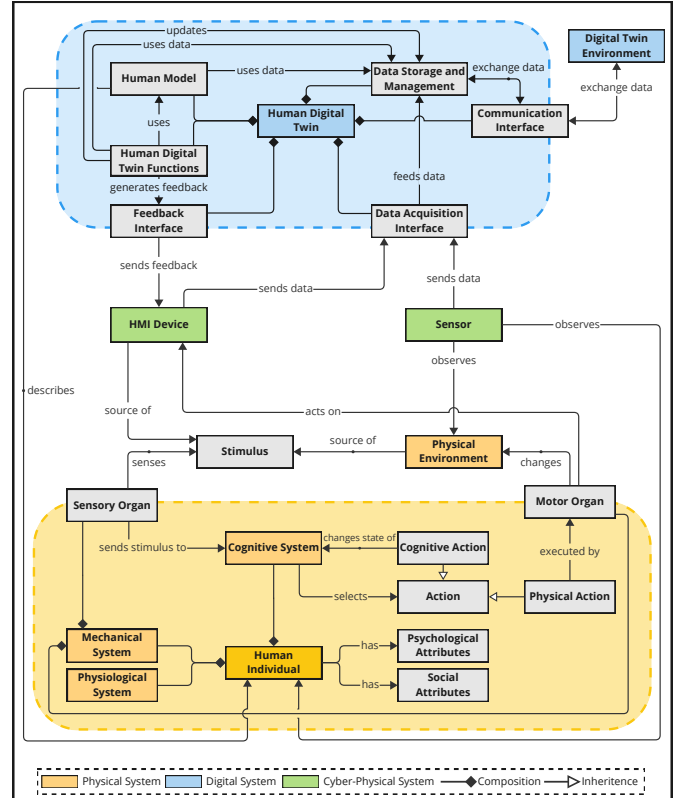


Fig. 7. Consolidated meta-model for the *Human Digital Twin*, *Human Individual* including the information transfers by both *Sensors* and *HMI Devices*

Figure 7 shows how *Sensors* and *HMI Devices* enable bi-directional data flow between human and HDT. *Sensors* observe both the *Human Individual* and *Environment*. This includes the physical actions that the human performs and their impact on the *Environment*. The produced data is sent to the HDT for emulation and feedback generation. Feedback is sent through *HMI Devices* which translates it into a physical signal, that manifests as a stimulus for the human which impacts their behaviour. The human may also choose to perform a physical action to send a message to the HDT through the *HMI Devices*. Finally, the *Communication Interface* enables the HDT to receive and share data with the Digital Twin Environment, composed of the other Digital Systems such as DTs of humans and machines, and direct communication with technical systems.

## 7. CONCLUSION

In this paper, we presented a meta-model for Human Digital Twins (HDT) based on general systems theory. HDTs require the close integration of digital, physical, and cyber-physical systems. The starting point of the paper is a general definition that defines an HDT as a class of Digital Twin (DT), that emulates the state and dynamics of a human, and is closely integrated through a bi-directional data flow. We identify and describe four systems that need to be integrated when developing an HDT; *(i)* a *Human Individual* is conceptualised as *Physical System*; *(ii)* the HDT is modelled as *Digital System* and described in terms of its components and interfaces that enable emulation; *(iii)* *Sensors* and *(iv)* *HMI Devices* are modelled as cyber-physical systems with the objective of bridging the physical and digital world, by transforming physical to digital signals and vice-versa. Each system is described in terms of components, boundary, interfaces, and objective.

Through the systemic description, this paper proposes a unified framework for HDT development. Clarified boundaries and interfaces can facilitate a more standardised approach to HDT implementations. In addition, we take a clear position on the role and placement of data sources and feedback mechanisms. Indeed, our model considers both of them as external to the HDT and human beings. The specified *Communication Interface* enables the HDT to connect to the larger digital environment. We hope to enable the development of flexible systems containing many (H)DTs to facilitate system-wide decision making while respecting the needs and state of human workers. The proposed systemic view enables the parallel development of DTs for each physical system. We envision a workflow where the interfaces and messages passed between systems can be decided during an initial conceptualisation phase, before parallel development of physical and digital systems can occur, finishing with integration of all systems. With standardised interfaces, pre-existing developments may be integrated into new systems and enable continuous progress for the field of Human Digital Twinning.

In this paper, we have not discussed the need for middle-ware or context brokers in large DT-based systems with an arbitrary number of participants and DTs. An expected challenge is the possibility that one sensor could provide relevant data to multiple DTs. In future research, we plan the implementation of a Human-Robot Collaboration scenario. Here, at least one human and one robot perform an assembly task. Through the use of DTs, we seek to enable the robot to adapt to human needs or behaviour. With this scenario, we seek to validate the merit of the systemic meta-model and will explore the applicability of technologies commonly used in the Internet of Things community.

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