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A Human Digital Twin for Worker-Centric Production

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Abstract

A human digital twin (HDT) is a virtual representation of a worker in cyberspace. Nevertheless, current research focusses mainly on HDTs for motoric work types, such as assembly. To fully integrate an HDT for workers in production, it is necessary that an HDT also displays cognitive processes like memorizing, thinking or reasoning. Such a concept can be used in information-based work, for example monitoring highly automated production systems, and contribute to the planning and control of production. Due to the high proportion of planning and decision-making processes, the efficiency of information-based work is determined in particular by the inner processes of the worker. An HDT can therefore help to describe current and future states of socio-technical work systems. Therefore, this paper presents a systematic literature review to explicitly derive the relevant components of an HDT for information-based work types. The elements of such an HDT and its environment are defined. Further, the current gaps in literature are identified. There are currently no real-world applications of such an HDT. Additionally, the value of multi-HDT systems must be evaluated more extensively.

Keywords: Human-centric Production; Digital Twin; Systematic Literature Review

1. Introduction

A digital twin (DT) is a digital representation of a physical object in the virtual world containing information about its physical twin [1]. The interconnection of DTs allows to track the current state of objects and even complex technical systems in real time and simulate their future states using algorithms or artificial intelligence (AI). In production, this enables the prediction of future machine conditions and improves decisions in maintenance or production planning.

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However, socio-technical work systems consist not only of physical objects and technical systems but also of at least one worker [2]. Without the integration of workers into the virtual world, a holistic representation of a socio-technical work system is not possible. Using only DTs, the prediction of future states becomes inadequate as the actions of the workers are considered in isolation or not at all. Workers cognitive and decision-making processes are complex, content-dependent and non-linear. The dynamic nature of human behavior, mental workload and decision-making varies under different conditions. As a result, the prediction of a socio-technical work system is incomplete or inaccurate.

This problem has already been recognized, and the human digital twin (HDT) has emerged. It was first mentioned in an engineering context in 2017 [3]. Since then, integrating workers into the digital world has become increasingly important [4–6]. HDTs are mainly described for work systems that involve a high proportion of energetic labor for the worker, such as walking or assembly [7,8]. In addition, some publications deal with reactive forms of work, such as driving a car [9,10], which require a balanced proportion of energetic and informational work. However, there is currently little literature describing the use of HDTs for information-based forms of work. Information-based work is characterized by the high proportion of thinking, memorizing, and reasoning skills required of the worker [2]. These skills cannot be observed, which makes it difficult to map the associated processes. In production, this includes, for example, the management and monitoring of a highly automated production system or decision-making for production planning or maintenance. Without the integration of these inner states of a worker, the HDT does not include the workers mental workload, judgement or behavior. Consequently, these models do not predict future states optimally. It is, therefore, not possible to digitally map and predict socio-technical work systems in their entirety.

This paper presents a systematic literature review (SLR) to identify suitable HDTs for complex inner processes of workers. The aim is to derive a holistic overview of such an HDT from literature, including its elements and its environment. Section 2 describes the methodology of the SLR. Next, Section 3 presents the derived HDT. Finally, Section 4 provides a conclusion and outlines future research.

2. Methodology

An SLR is conducted to derive an HDT model for information-based work forms in production. The SLR is based on the PRISMA 2020 checklist [11]. It includes all journal articles and conference papers that have been accepted or have a higher publication status. The SLR was conducted from 29.08.2023 until 14.09.2023 in English and German. The databases Web of Science - Core Collection (WoS-CC) (webofscience.com), Wiso (wiso-net.de), IEEEexplore (ieeexplore.ieee.org), Scopus (scopus.com), ACM Digital Library (https://dl.acm.org/) and Google Scholar (scholar.google.com) were used. The databases were chosen in reference to the publication of Gusenbauer and Haddaway [12], where it is stated that all of these databases, except Google Scholar, allow repeatable searches over time. Further, the chosen databases are either multidisciplinary or in computer science, which helps to retrieve a wide variety of publications. Whenever possible, the search terms were limited to German and English. Further, it was, whenever possible, limited to abstract, title, and keywords.

The search strategy was first defined to identify suitable articles. The SLR aims to identify approaches that present a definition, a framework, a concept, or an architecture for an HDT for information-based work. Suitable articles allow to derive a definition of the HDT. Since the term HDT is relatively new, the search term was defined as broadly as possible, and no application field was defined. The term "shadow" was also included since it is known to the authors that the term digital shadow is used as a synonym for digital twins [13]. Therefore, the following term was chosen: (Human AND Digital AND (Twin OR Shadow)) OR Menschmodell.

WoS-CC was used as a reference database to check whether the search term was appropriate and well-suited to identify publications presenting a definition, framework, concept, or architecture for an HDT. This database was chosen because it has an article inventory of over 70 million articles and is multidisciplinary [12]. Therefore, it is an ideal starting point to evaluate the quality of the search term. The search results obtained are displayed graphically using VOSviewer. VOSviewer is a free program to perform bibliometric analyses and display their results in figures [14]. The program was used to identify and map the co-occurrence of keywords in all articles retrieved from the database. It analyses whether the keyword is present in an article or not. The more articles that contain this keyword, the larger the keyword is displayed in the graphic. In addition, keywords that occur together in articles are connected by lines that get thicker the more often those keywords arise together. Fig. 1 shows the co-occurrence of keywords in the articles. Only keywords that appear in at least twenty articles are displayed.

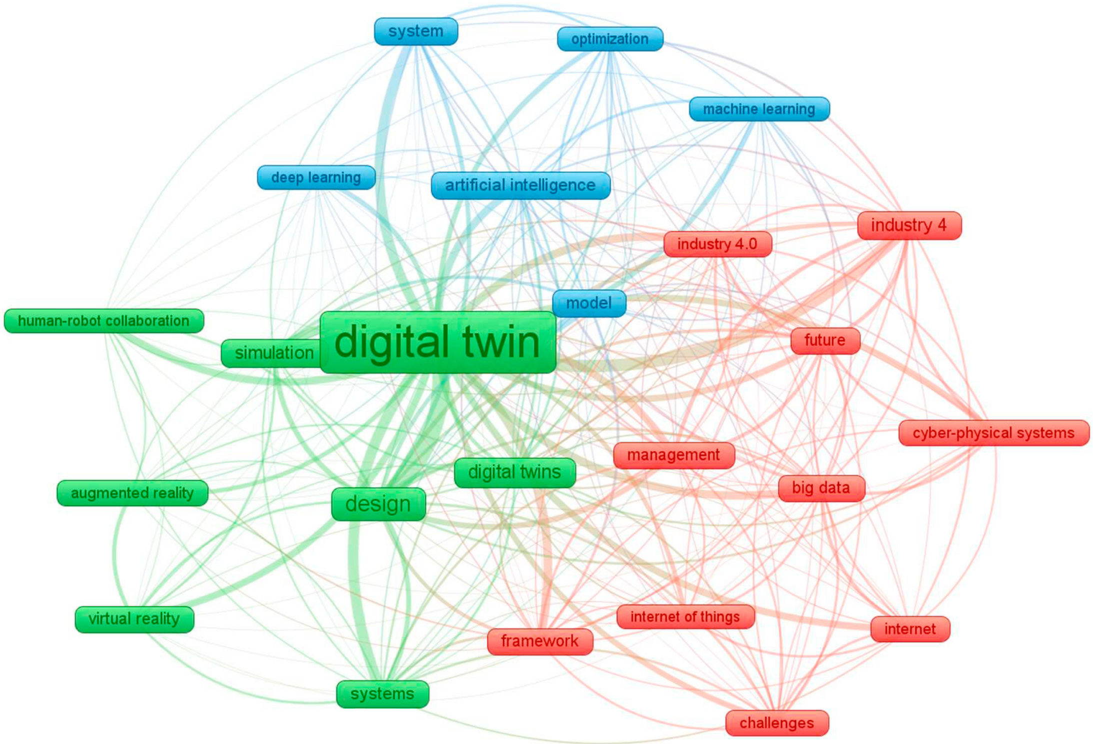

Fig. 1. Co-occurrence of keywords.

The keywords “industry 4.0”, “digital twin”, and “simulation” or “virtual reality” gave confidence in the suitability of the search term. The search pass ascertained 2216 publications, screened first by title, then by abstract, and afterward by full text. The inclusion criteria must all be fulfilled:

- The approach focuses on defining or describing an HDT or presenting a framework, an architecture, a concept, or a model, in which the worker is displayed as the main element
- It mainly deals with information-based work types, such as decision-making or cognitive behavior
- It is in the context of manufacturing, production area or product development

If an article does not fulfill all these inclusion criteria, it was excluded. Additionally, an article was excluded if the following criteria are fulfilled:

- The article does not focus on defining or describing an HDT or presenting a framework, an architecture, or a model where humans or workers are the main elements but instead technical systems

Fig. 2 shows the selection process in detail. Ten articles were identified for the qualitative synthesis. Further, a backward citation search added one relevant article to the qualitative synthesis. No articles were included through a forward citation search. Table 1 lists the identified articles.

Table 1. Identified articles.

Miller and Spatz [15]	Shengli [16]	Löcklin et al. [17]	Ariansyaha et al. [18]
Naudet et al. [19]	Saariluoma et al. [20]	Naudet et al. [21]	Sparrow et al. [22]
Bousdekis et al. [23]	Graessler and Poehler [3]	Song [24]	

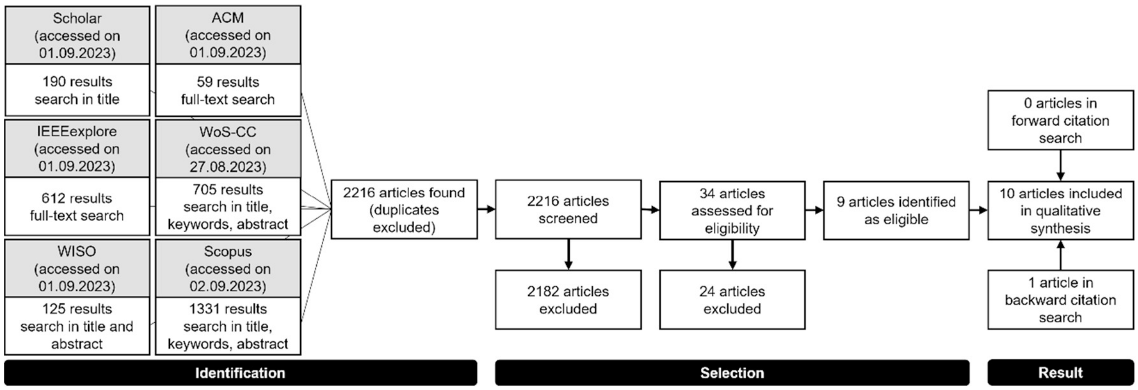

Fig. 2. Selection process.

Interrater reliability is determined to measure the reproducibility of the SLR based on the defined inclusion and exclusion criteria. Cohen's kappa (κ) is used to measure interrater reliability [25]. This statistical measure is used to calculate interrater reliability when two people or reviews are conducted. The value can range from -1 to 1, although values between 0 and 1 are common in practice [25].

Table 2a shows the scheme of the collected data to calculate κ. The search results of the databases were scored either with a "1" or a "0" by the raters. If the article was excluded, it was assigned a "0". Suitable articles were scored with a "1" by the first reviewer x_1 and the second reviewer x_2. n describes the search results identified from the databases. $\sum x_{1,0}$ describes all articles identified as not suitable from x_1. For x_2, this is represented by $\sum x_{2,0}$. The sum of suitable items is represented by $\sum x_{1,1}$ for x_1 and $\sum x_{2,1}$ for x_2. $n_{0,0}$ is the number of items rated as not suitable by both x_1 and x_2. Whereas $n_{1,1}$ represents the number of items rated as suitable by both raters. Items identified as suitable by x_1 but unsuitable by x_2 are represented by $n_{1,0}$. The items identified as unsuitable by x_1 but as suitable by x_2 are mapped as $n_{0,1}$.

Table 2b shows the data to calculate interrater reliability. Two persons evaluated the 2216 search results of all databases. The search results were independently checked with the respective criteria for title and abstract so that the full texts were identified. A κ value of 0.81 is calculated from the data. A confidence level of 95% is assumed. The calculated lower limit of the confidence interval is 0.7, and the upper limit is 0.92. κ is, consequently, between 0.7 and 0.92, with a probability of 95%. A value of 0.7 indicates moderate agreement [25], from which it can be deduced that the defined criteria for the title and abstract are suitable, and the SLR is reproducible.

Table 2. Scheme for interrater reliability (a) and data for interrater reliability (b).

		x_1		Sum
		0	*1*	
x_2	*0*	$n_{0,0}$	$n_{1,0}$	$\sum x2_0$
	1	$n_{0,1}$	$n_{1,1}$	$\sum x2_1$
Sum		$\sum x1_0$	$\sum x1_1$	n

(a)

		Rater 1		Sum
		0	*1*	
Rater 2	*0*	2178	8	2186
	1	4	26	30
Sum		2182	34	**2216**

(b)

A qualitative content analysis was conducted to extract the articles' key aspects and identify the research gap. The deductive category application technique was applied [26]. A content structuring of the articles was performed. The categories and their definitions are shown in Table 3. The specifications of each defined category are presented in Table 4.

Table 3. Category system with definitions.

Category	Definition
Objectives	The aim of the article.
Methodology	The methods used to derive a definition for the HDT.
Fields of research	The engineering area, wherefore the HDT is described.
Evaluation	The validation process of the HDT concept, framework, or model.
Future work	Further work is necessary to improve the article's results.
Definition of an HDT	A short and precise description of the HDT.
Elements of an HDT	The elements an HDT consists of.
HDT environment	The elements with which the HDT communicates and which are in its direct environment.
Human data	The data that the HDT stores, collects, or processes.

Table 4. Category system with specifications.

Defined Categories		Specifications
Definition	What is it?	Not stated; Digital representation of a human; A copy in cyberspace of a person; A cyber-physical device; Subclass of a digital twin; Model; Database
	Where is it?	In a specific context; in a real-world environment
	What does it do?	Data acquisition; Prediction; Description; Analyzation
	What does it contain?	Characteristics; Behavior; Preferences; Skills; Information; Requirements; Expectations; Work schedule
HDT Environment		Not stated; Digital twin; Virtual representation; Human; Physical representation; Two-way communication; Human digital twin system; Environment; Data Lake; Library
Elements		Sensors; Actuators; Database; Models; Artificial intelligence; Internal process; Prediction engine; Objective; Task; Interface; Input element; Feedback element; Security mechanisms
Collected Data		No specifications defined

3. Results

3.1. Research Gap

Miller and Spatz [15] define the terminology of the HDT and present use cases for an HDT in product development. In July 2021, they conducted an SLR and retrieved 54 publications dealing with HDTs. Most of these identified articles are written in the fields of manufacturing or medicine. Based on these publications, they derive a terminology. The HDT from Miller and Spatz [15] is mainly defined based on existing definitions of motoric and mechanical work types. This research primarily focuses on information-based work types. Hence, the outcome can differ since the HDT is an application-specific topic. Löcklin et al. [17] analyze the potential of an HDT for manufacturing and intralogistics. As a result, they develop a reference architecture for this application field. Ariansyaha et al. [18] create a framework to integrate humans in a digital twin for industry and manufacturing applications to improve production planning and resource distribution. Sparrow et al. [22] explain the need for a digital administration shell for workers in production systems. Thereby, they define the term HDT and its elements. Bousdekis et al. [23] show Operator 4.0 as a digital administration shell consisting of an HDT. Graessler and Poehler [3] present a definition and an approach to integrating a worker into the cyber-physical production system. They integrate data to create a model of the worker's characteristics. Contrary to most publications, the framework from Song [24] contains a data lake and a library. These are elements that include general models or aspects that humans have in common or a collection of one human's data, which can be used in several HDT models. Thereby, he already focuses on the implementation of a group of HDTs and the value that can be created with multiple HDTs.

Shengli [16] aims to analyze whether an HDT is technically possible. Therefore, he presents a technical framework on how to implement an HDT for the whole life of a human. The idea is based on the medical application field, where an HDT should accompany a human throughout life. As a result, he mentions that with the fast-evolving technology, especially regarding storage and data processing, it is technically possible to develop an HDT for real-time data collection and analysis. Nevertheless, the currently available technologies must evolve before such an HDT can be implemented realistically. Saariluoma et al. [20] provide a very abstract view of the HDT and propose a design framework for modeling an HDT. The authors state that this concept cannot be used for any industrial context since the model is too abstract. Therefore, this model is excluded from the analysis. Naudet et al. [21] present a generic definition based on a literature review from their previous article from 2021 [19]. Nevertheless, in both articles it is not clear how the definition was retrieved from the literature because the conducted literature review was not presented systematically. Furthermore, the literature review was probably executed in 2021 and, therefore, must be updated with recently published research.

Regarding the found publications the following research gaps were identified:

- Application-Specific Definitions of HDTs: There is a lack of a definition or framework that can be applied to broader contexts or application scenarios.
- Lack of HDTs for information-based work types: Existing definitions might not fully capture the needs of information-based work scenarios.
- Technical Feasibility: No real-world evaluations have been conducted yet.
- Multi-HDT Systems: Research mainly focusses of the concept of one HDT. Although, using multiple HDTs creates more value for production.

In conclusion, there is currently no publication that focuses on information-based work types for workers. Consequently, production processes, which require decision-making, memorizing or further complex cognitive skills, are not considered in HDTs models properly. Hence, this article differs from already existing concepts for HDTs because it highlights relevant elements of HDTs for information-based work. Table 5 differentiates the literature from this publication. It shows which parts of this research are covered in the retrieved publications.

Table 5. Currently existing research gap.

Category and specification of this publication	Article number										
	[15]	[16]	[17]	[18]	[19]	[20]	[21]	[22]	[23]	[3]	[24]
Application field: Information-based work	◕	○	○	○	○	○	○	○	○	○	○
Objective: A concept for an HDT	●	◔	◔	◑	◑	○	◑	○	○	◑	●
Methodology: Systematic literature review	●	○	○	○	◑	○	◑	○	○	○	○
Outcome: Concept of an HDT, its elements, and the environment	◕	◔	◔	◑	●	○	●	◑	◑	◑	◕

Symbols

○	◔	◑	◕	●
Not covered	**Slightly covered**	**Partly covered**	**Almost covered**	**Fully covered**

3.2. Human Digital Twin

Five out of eleven articles describe an HDT as the digital representation of a human. Shengli [16] describes an HDT as a copy of a human in cyberspace. The author especially states with the word “copy” that the HDT duplicates all aspects of a human, whereas most authors use the word “representation” [15,17,21,23,24]. This indicates that not all aspects of a worker must be modeled but that specific characteristics or behaviors are mapped digitally. Naudet et al. [19,21] describe an HDT as a subclass of a DT where the twinned entity is a human being. The authors present an HDT model with UML notation derived from a DT. Therefore, the authors also state that an HDT is a digital representation of a human. The oldest publication of an HDT is from Graessler and Poehler [3]. They describe an HDT as a database of a worker for assembly planning. It allows the prediction of future states of the assembly tasks based on predefined rules. Since this publication is the first to mention an HDT, this article can be seen as the origin of the HDT. Since this is the first publication of the HDT, the concept is supplemented by the other publications and must be seen as a first draft. Therefore, the HDT presented by Graessler and Poehler [3] is missing certain aspects described in the following paragraphs. Miller and Spatz [15] and Shengli [16] highlight that an HDT is a model and, therefore, a human replica. Hence, it is emphasized that the human is the central element of the HDT concept. The HDT can only exist together with an associated human being. Consequently, the HDT aims not to replace humans but to benefit humans by advancing digitization [17].

The HDT provides feedback to workers or predicts possible future states of the worker [16,18]. Therefore, it collects data from humans and processes it with integrated context-specific models [17,18]. Hence, the advantages of an HDT can be specified as data collection through sensors, digital description of the worker based on the collected data, data analysis, prediction of possible future states, and analysis of past behavior. Whereby only Bousdekis et al.

[23] explicitly highlight the aspect of data analysis. In other publications, this is only indicated or implied.

The collected data can be of any kind. The authors state different possible categories, e.g., characteristics, behaviors, skills, or preferences. Further, more situation-specific data can be collected. For example, Graessler and Poehler [3] collect the assembly workers' favorite tasks, intrinsic and extrinsic motivation, and work schedules. With these HDTs, they optimize production planning and use these data to enhance the individual's perceived work quality and the work environment. They highlight that an HDT must be used in a system of multiple HDTs and DTs to generate value. Otherwise, the benefits of such an HDT cannot be fully obtained because they are limited to feedback and predictions without considering the environmental circumstances of the worker. Hence, the whole socio-technical system must be considered.

The HDT must collect and analyze data from the worker and their environment to predict future states and provide feedback. As the amount and quality of data increases, so does the need for storage capacity. Many factors must be considered to analyze and predict worker's behavior; therefore, a large amount of data must be obtained from the worker. Hence, different data collection concepts must be applied. Considering these aspects, Bousdekis et al. [23], Naudet et al. [19], and Song [24] state that the HDT must be currently limited to a precisely defined application field or use case. This reduces the necessary amount of data and allows predictions and analyses. Nevertheless, as an outlook, it could be possible to create HDTs that are used for multiple use cases. Further, collecting only the needed data and as little as necessary is recommended to counteract privacy issues. The importance of privacy and regulated access to an HDT is stated by Löcklin et al. [17], Shengli [16], and Naudet et al. [21]. Nevertheless, the idea of the HDT is to connect with other DTs and HDTs to exchange information and provide new insights and predictions [19,21]. Therefore, the HDT must contain all necessary data to allow this exchange. Hence, it is essential to understand the context and situations in which the HDT is used. Based on this context, data from the human must be collected. Based on the conducted analysis, the following definition of an HDT is derived:

"An HDT is a digital representation of a worker. It describes the worker, analyses collected human data and uses it to predict future states and provide feedback about past behavior. The HDT is created for a specific context in which it generates value. The HDT communicates with other DTs and HDTs in its environment and provides feedback to its worker."

An HDT can be seen as a subclass of a DT that is a replica of a worker. Human data is sensible and must be secured against unauthorized access or misuse. Regarding these security aspects, an HDT should be modeled for a specifically defined context to collect only the required data from the worker. When every worker has its own HDT, these HDTs can communicate with each other and other DTs of technical systems to emulate the physical world. This can enhance processes that rely on groups or socio-technical systems. Thereby, value is created because simulations can be conducted, and recommendations are generated to improve the processes.

Miller and Spatz [15], Naudet et al. [19,21], and Bousdekis et al. [23] explicitly describe the environment of an HDT. This environment can also be called the system in which an HDT operates and interacts. Such an environment contains the HDT and describes all relations to other elements or entities in the physical or virtual world. Seven articles describe a digital twin or a virtual representation as the main element. This element is connected or relates to a worker or a physical representation. Further, these articles describe the importance of two-way communication between the worker and the HDT. Naudet et al. [19,21] emphasize that this communication must be real-time to simulate the human's future behavior. Five articles highlight the importance of the environment of the worker and the HDT. This environment exists in the virtual as well as in the physical world. The worker is affected by other workers and technical systems. This must be displayed in the virtual world by the HDT. Therefore, the HDT must be related to other DTs and HDTs. It is affected by them and affects them [19,21]. Shengli [16] states that a human is in an environment with other humans. This must also be displayed in the cyberspace. Therefore, there is never one HDT alone; there are multiple HDTs and their environment. This highlights the importance of group behavior and the influence of groups, which must be considered when modeling HDTs. Song [24] presents a different view of the HDT system with additional elements: the data lake and a library. In the data lake data from multiple workers is captured, which HDTs can access. These HDTs can emulate specific aspects of this data collection and, therefore, can access the needed models from a library. Graessler and Poehler [3] do not mention the environment of an HDT. Based on the qualitative content analysis, the most relevant aspects for the environment of an HDT are (see Fig. 3):

- The worker, which is represented in the digital world.

- The HDT itself, which represents the worker in the virtual world.
- The physical world, in which workers and technical systems exist.
- The virtual world in which other HDTs and DTs exist.
- A bi-directional communication between the worker and its HDT.
- Communication between the assets of the virtual world and between the workers and systems in the physical world.

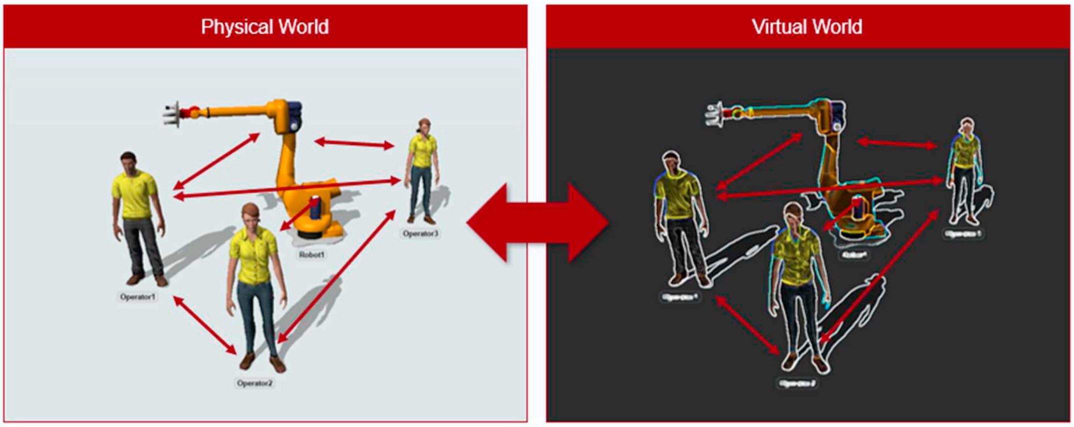

Fig. 3. The defined HDT system as a 3D illustration created with FlexSim.

Six articles agree that sensors are needed to collect human data. These sensors can also allow data collection in real-time so that the HDT can make predictions in real-time for the human [19]. Miller and Spatz [15] and Bousdekis et al. [23] state that the worker can add additional data through an input element. This can be data that is not easy to measure through sensors or static data, such as the name. Seven articles mention an interface where humans can access and change their data. Further, four articles mention such an interface for feedback from the HDT to the human. Therefore, the HDT needs an interface that allows feedback and data access. Such an interface allows two-way communication between a human and its HDT.

Löcklin et al. [17] mention the importance of access rights for the data. This allows humans to secure their data against unauthorized access by others. A database is needed for the data as a central element of the HDT [21]. The importance of a database is stated in six articles. Further, six articles point out that underlying models inside the HDT are needed to model human behavior (e.g., [15]). Algorithms are required to make predictions and provide feedback. AI can improve these algorithms [16]. Miller and Spatz [15] and Shengli et al. [16] state that a human has a specific goal or objective he wants to achieve. To achieve this goal, humans do a task. These tasks and objectives must also be modeled in the HDT because humans do tasks to achieve their goals. If this is not regarded in the HDT, the HDT will make wrong predictions of future states or provide false feedback because the HDT does not know how to support humans optimally. Fig. 4 presents the identified HDT elements in the articles. Based on the analysis, the following elements for an HDT are relevant and highlighted:

- Sensors to collect real-time data.
- A database to store the collected data.
- Models that model specific aspects of human behavior.
- AI will predict future states and provide feedback.
- An interface that allows input data and feedback to be provided.
- Security mechanisms that prohibit unauthorized access.

Shengli [16] and Naudet et al. [19] emphasize the importance of a unique ID for an HDT. This is especially important because an HDT is an individual representation of one specific worker. Therefore, it must be guaranteed that the correct data is collected and provided to the right HDT. Otherwise, predicting future states for humans or providing individual feedback is impossible. Further, data must be collected use-case-based, wherefore these categories could also be collected: physiological data, physical data, skills, moods, preferences, emotions, and performance data.

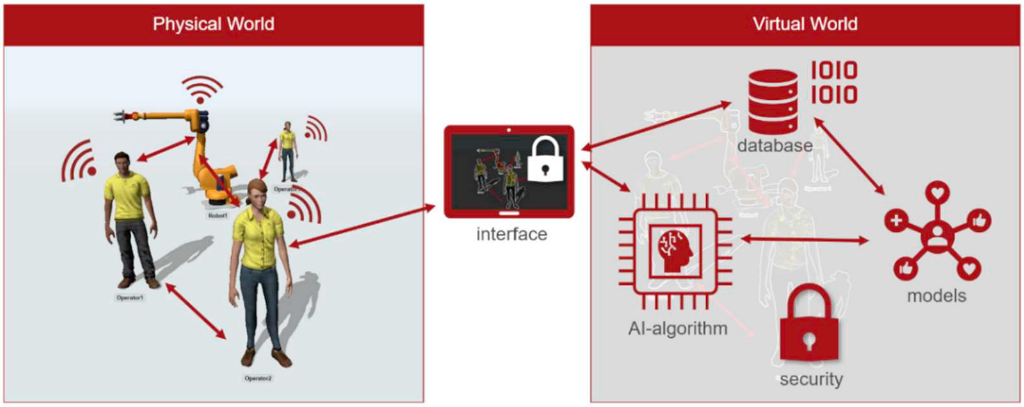

Fig. 4. The HDT as a 3D illustration created with FlexSim.

4. Conclusion and Future Research

4.1. Conclusion

This paper analyzes the current literature to identify and present relevant aspects of an HDT for information-based work types. In conclusion, the following describes the understanding of an HDT: An HDT is a digital representation of a worker that models aspects of the behavior, characteristics, emotions and further data for a specific context. The integration of physical and physiological data of the worker in real-time enables the prediction of future states and individual feedback. Therefore, data is collected using sensors, stored in a database and analyzed with algorithms and AI. This allows for insights of the interaction between the worker and its work environment. One HDT belongs to one worker to maintain privacy and security. The HDT and the worker can communicate with each other via an interface. Further, an HDT communicates with other DTs and HDTs in its environment. Thereby, value is created because the use of a multi-DT-HDT system allows for simulations and optimizations, enhancing both individual and collective human performance in specific applications.

4.2. Discussion and Future Research

It is essential to note limitations concerning the SLR and the identified concepts. The SLR does not focus on the permutation of search terms, such as the NEAR operator and search terms like 'Zwilling' in German. Further, humans are more complex than technical systems, and a comprehensive digital representation must include various dimensions, which must be identified first. An empirical validation must be conducted first to prove the suitability of such an HDT in production.

Future work will focus on the derivation of requirements for an HDT. These use cases will consider real-world problems in manufacturing environments. Therefore, case studies and pilot projects in companies will be conducted. The use cases form the basis for describing and evaluating the benefits to be achieved with an HDT. The technical realization of the HDT has not been considered yet. The future research question is: To what extent is it possible to digitally represent a worker with an HDT so that the behavior can be analyzed, and appropriate feedback can be given regarding use cases in production? Hence, future work will focus on empirical validation and research in real-world production environments, including research on security and privacy aspects as well. Lastly, future work will also consider multi-HDT systems to enhance the productivity of whole production environments. Thereby, the benefits of the HDT in teamwork settings also need to be elaborated. It is crucial to prove the generalizability of the found definition, at least for the production area. Finally, further research and regulatory discussions are necessary regarding privacy concerns for real-world application, as a broad application in practice will be challenging.

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