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# Towards a Holistic Framework for Digital Twins of Human-Machine Systems

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**Abstract:** This article goes back to the origin of Digital Twin (DT) concepts, contextualizes their emergence and highlights their main key points. Models of DT are discussed with regard to nine criteria: physical asset, model, communication, service, data, product, autonomy, environment, and human. Criteria like autonomy, environment and human are rarely studied in terms of shared control between humans and machines or in terms of user surroundings integration while Human-Centered System Design approaches exist. Few of models studied consider humans as a physical part of Human-Machine Systems (HMS). Similarly to a Machine Digital Twin, it is proposed to realized a Human Digital Twin for modelling the human part of HMS. Therefore, design guidelines, solutions and a new framework are proposed to set the pace for a new generation of Digital Twins. They are based on new Human-Machine interaction concepts and on different design modes applied to a Digital Twin of Human-Machine System.

*Keywords:* Digital Twin, Operator 4.0, Human-Centered Design, Holistic Framework.

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## 1. INTRODUCTION

Despite a multiple nomenclature (*“Industry 4.0”, “Smart Manufacturing”, “Society 5.0”, “Made in China 2025”, “Industry of the Future”, etc.*), the fourth industrial revolution is definitely present and each country has a common and unique goal, mesh the virtual world to the real world. Thanks to new Information Technologies (IT) and Operational Technologies (OT), data availability, real-time connection and synchronization of data, the application of Industry 4.0 concepts is feasible. According to a Deloitte press series on Industry 4.0 (Parrott and Warshaw, 2017), the Physical-Digital-Physical Loop can be achieved too. The P-D-P Loop consists to record and capture data from physical space, then, use it in digital space to finally generate actions in physical space according to the analysis and treatments done by the digital part. This loop allowed the emergence of Digital Twins (DTs), a new trend for a variety of needs in several fields. In recent years, due to this trend effect, several design models have settled into the Digital Twin sector. This model-based design race has allowed the research and development of Digital Twins to progress but not enough. Indeed, future DTs have to consider not only machines but also users as a holistic physical part of a Human-Machine System (HMS). In this context, this article will focus on Human-Centered based solutions to improve the design of new generations of Digital Twin based on a holistic framework. The following paper is structured as follows. Section 2 is dedicated to the origins of Digital Twin concepts and a study on DT architectures is realized. Section 3 focuses on Digital Twin autonomy and environment which are characteristics that are rarely found in DT reviews. This section also presents

a Human Digital Twin concept for a human consideration in all future Human-Machine System. Finally all characteristics are mesh in section 4 and a Holistic Framework is proposed to frame the new generation of Digital Twins.

## 2. DIGITAL TWIN MODELS

The development of Digital Twin concept is traced back in 1970s, when NASA launched Apollo Program with multiples simulators and replicas of vehicles in their buildings to allow mirroring the conditions of the mission, including failure scenarios (Ferguson, 2020). In 2003, Grieves was the first, to introduce the term of Digital Twin in a Product Life-cycle Management (PLM) course (Grieves, 2015). PLM unifies the business activities of a company that generate, manipulate and use data to support all stages of the product life-cycle. Indeed, Digital Twins can be compared to Cyber-Physical Systems (CPS) except that they focus more on virtual models while CPS emphasize computing, controlling and communications capabilities. Grieves said that before manufacturers used digital space and physical space separately and Human had to do the linkage. Digital Twin allows now to use both parts concurrently with real-time synchronization between them, that’s why DTs are real solutions for the fourth industrial revolution needs. A Digital Twin needs a physical twin (an asset or a machine) to operate. Then, data flows between the asset, its digital space and every structure that needs access to the twin. Every Digital Twin will involve several flows of information between the physical object and its digital part, but also between the twin and the enterprise systems such as Enterprise Resource Planning (ERP), Manufacturing Execution System (MES) or Product Life-

cycle Management (PLM) (Semeraro et al., 2021). Besides, the more advanced analytic and simulations will perform through the Digital Twin, the more people will be involved in the process (Slevin, 2018).

Over this definition, Minerva and Crespi (2020) can assume that all DT have the same properties and capabilities. They listed eleven points that make a system a Digital Twin. In order to agree with everyone on a general definition of the Digital Twin, it was decided to carry out a study of different Digital Twins in the scientific literature in order to identify the features that really specify them. The study was based on fifteen publications, both academic and industrial about Digital Twin of assets, processes and other Human-Machine Systems. After each reading of the article, the authors explicitly or implicitly noted the important points of each digital twin design. Then, global characteristics emerged and a table was created to summarise the results. These results are confirmed by various state-of-the-art studies on DTs that the authors have read.

Ref.	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Van Der Valk et al. (2021)	•	•	•	•	•		•		•
Jazdi et al. (2021)	•	•	•	•	•		•	•	
Zhang et al. (2021)	•	•	•	•	•	•	•		
Sturm et al. (2021)	•	•	•	•	•	•		•	
Semeraro et al. (2021)	•	•	•	•	•			•	
Minerva and Crespi (2020)	•	•	•	•	•	•	•	•	
Sharma et al. (2020)	•	•	•	•	•		•		•
Liu et al. (2020)	•	•	•	•	•	•	•		•
Stark et al. (2019)	•	•	•	•	•		•	•	•
Seal (2018)	•	•	•	•		•			
Tao et al. (2018)	•	•	•	•	•				
Parrott and Warshaw (2017)	•	•	•	•	•				
Rosen et al. (2015)	•	•	•	•			•	•	
Ríos et al. (2015)	•	•	•				•		
Grieves (2015)	•	•	•						

(1) = Physical Asset      (4) = Services      (7) = Autonomy  
(2) = Models              (5) = Data              (8) = Environment  
(3) = Communications    (6) = Product          (9) = User

Fig. 1. Adjacency Matrix of DT characteristics in literature

In Figure 1 each number " $i$ " corresponds to a specific " $i$ " characteristic of the Digital Twin. The following characteristics have emerged: (1) the PHYSICAL ASSET to twin ; (2) MODELS of the asset (digital part) ; (3) COMMUNICATIONS between models and the asset ; (4) SERVICES like simulations, predictions, diagnosis (purposes of the DT) ; (5) a DATA system (preprocess, storage, extraction, management, etc.) ; (6) a PRODUCT life-cycle consideration (involves a certain flexibility of the DT) ; (7) an AUTONOMY of the DT (Update, Self-Manageability) ; (8) a CONTEXT/ENVIRONMENT consideration and integration ; (9) HUMAN interest in the whole HMS.

The first relevant point of this study is the presence of (1), (2) and (3) characteristics in every Digital Twins inspected. A machine, a model and links between both seems to be the elementary parts of a DT. Indeed, this is a result of its origin defined initially by Grieves (2015). According to the P-D-P Loop, he defines a Digital Twin mainly as a composition of 3 elements: Physical part, Virtual part, and a flow of data between the physical and virtual

parts. Most of reviews and states of the art on Digital Twin claims Grieves architecture (Semeraro et al., 2021). Grieves launched a race to define the Digital Twin. Since 2015, a phase of development of Digital Twins has begun (Tao et al., 2019). Fei Tao and Rainer Stark are the ones who quickly established themselves with each a model and new feature. As example, Tao et al. (2018) proposed a 5-Dimension Digital Twin model. Based on the 3-Dimension Grieves model, they added the newly dimensions of Data (4) and Services (5). In the process of interaction between digital and physical spaces, the integration of data is an unavoidable point to consider. The data from reality are transmitted to the virtual twin through the sensors to complete the simulation, validation and dynamic adjustment. The simulation data are feedback to the physical entity to respond to the changes, improve the operation, and increase the value. Added to this, services enable numerous large-scale manufacturing collaboration. Therefore, Digital Twin, big data and services can be united to promote smart manufacturing.

According to Stark et al. (2019), a Digital Twin is the digital representation of an asset (product, machine) that determines its properties, condition and behavior by means of models, information and data. In contrast to Tao et al., their definition is a little different. From Stark et al. point of view, Digital Twins are designed for use in designing, prototyping, and manipulating virtual copies of products thanks to real-time data. Here the trend is more about manufacturing with a DT developed for the whole product life-cycle. So, they decomposed the model into eight characteristics. Digital Twin context and environment is represented by the four first dimensions: integration breadth (8), connection mode (3), update frequency (7) and product life-cycle (6). Finally, CPS intelligence (1), the simulation capabilities (4), the digital model richness (2) and the human interaction (9) correspond to the four last dimensions as the DT behavior and its capability richness (Riedelsheimer et al., 2020). This last architecture involves eight of the nine main point relieved in the Digital Twin study.

As discussed above, since few years, more precise models and new trends are established in the academic field in order to structure the Digital Twin design. But some manufacturers take part of this new "4.0" dynamic too. One example is Boeing, which has invented a new way to depict the design and production of their products by revolutionizing the classic "V" representation of systems engineering (Seal, 2018). The Boeing Diamond represents a connected environment between the virtual modelled world and the physical world at any time of the Boeing product life-cycle. The bottom-half represents Physical System, retaining traditional system engineering "V" flow, and the top-half represents the Digital Twins. The link between models/simulations and the physical systems is realized by the Digital Thread. Digital Thread is different than a DT it corresponds to the flows of data between each space and it helps the twin to be operational. In this architecture, Digital Twins integrate methods as machine learning and data analytic to create digital simulation models that update and change as their physical part change. A Digital Twin continuously learns and updates itself using multiple sources to represent its status, working

condition, or position in near real time. Each private entity (companies, researchers, or private labs) has their own representations of Digital Twins and their own solution to mesh virtual and physical worlds. In fact, this is difficult to find an ended definition of the Digital Twin, as the term is still in a state of transformation and as depending on the field of research.

What emerges from this study is the low presence of features (7), (8) and (9), respectively reflecting the autonomy of the DT, the consideration of its environment and its user in the DT design. Whatever method is used to design the digital part of a Digital Twin, it must be well realized and as representative of the real system as possible. Of course, if it is initially not well designed, a Digital Twin could present some problems in its use and results. That is why, it is so important to take aware of each aspect of the machine to model such as primary functions and tasks, human integration in the whole system, or even the use of the Digital Twin too. As it is mentioned in Vanderhaegen (2017) and Vanderhaegen (2021a), the long-term use of autonomous systems can degrade the ability of operator to react due to a lack of attention when they have to take back control or when their real goals interfere with those of the system as Digital Twin. This degradation of situation awareness is primarily caused by wrong design of Intelligent System model and especially Human-System integration in a context of autonomy of the DT as well as the consideration of the machine’s operator and her/his environment.

### 3. HUMAN-CENTERED APPROACHES FOR DIGITAL TWIN

#### 3.1 Holistic concept of Human-Machine System

As shown in the previous section, consideration of DT’s autonomy, its environment and its user are little considered in DT design despite the fact that they could considerably improve them. As new systems, Digital Twin need to be smart, resilient, green, safe, reliable, efficient, interoperable, connected, sustainable and autonomous. This goal is reminiscent of the “All-Inclusive” concept from (Vanderhaegen, 2021b) to developed future systems capable of adapting to human demands whatever the cognitive and physical capacity of the users. The purpose of designing a Digital Twin is to provide a service to the user. Generally, this involves information on the state of the physical system, but also predictions, diagnosis, simulations or even corrective tasks and actions back to the physical side. To fill the gaps of some previous developed models, these three elements can be added to the five-dimensions model from Tao et al. (2018) into a Holistic Framework for Human-Machine System Digital Twin. This Holistic Framework represented in Figure 2 has to be used to design a DT of Human-Machine Systems and it aims at including environmental constraints, shared autonomy principle and finally most of human’ parts of the system. In the proposed Holistic Framework, human is consider as a physical entity of the global system to digitalize. A human’s behavior is integrated digitally and communication devices aims to animate respective models. Machine and Human models will feed services to the DT user (simulations and predictions) and also the decisions part which realize a shared-control

between three parts: the human operator, the machine and the Digital Twin.

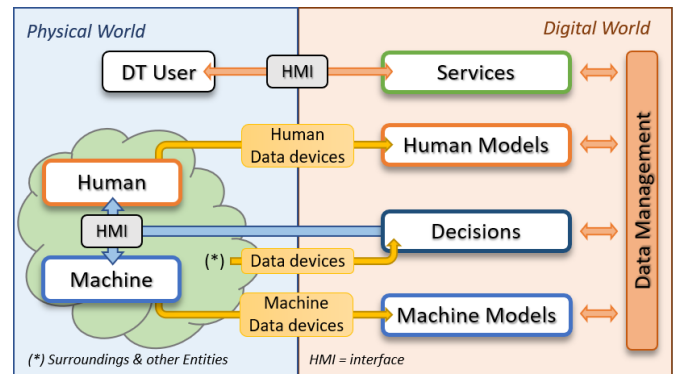


Fig. 2. Holistic Framework for Human-Machine DT

Digital Twins were firstly created for development and manufacturing purposes, they are now design to better understand complex systems. An extraction of the human from the whole Digital Twin design is necessary. The human is at two levels in an HMS DT, of course in the human models of the HMS but also at the user level.

Firstly, the human is present in the whole Human-Machine System as an inseparable part of the system. When it comes to modeling a HMS, it is not only about the physical object but also about the human being and the links between both. There, Human models can be set up based on Artificial Intelligence in order to mimic human capabilities (Saariluoma et al., 2021). These Human models are a kind different than Machine models because humans have not the same skills, interactions and activities than assets. Some have already tried to create a Digital Twin of a human being either for medical patient management issues (Wei, 2021) or for human-machine system design reasons (Baskaran et al., 2019). The goal here is not to take into account only the machine or only the human but all the elements that compose the system. Secondly, there is a human who takes the role of user and interacts with the DT through its Services part. It is necessary to take into account the fact that designing a Digital Twin is above all to meet a need, especially a need for a user. Services and Decisions parts depend on the intended objectives of designing the DT. Sometimes, the DT user is the same person as the Human Operator who interacts directly with the Machine and its environment. In that case, user services and decisions that could be take on the HMS form both a single block. It is then possible to imagine interfaces between the human and the intelligent system that would provide information on the scope of action of each (authority decisions and task dispatcher) and predictions on the future state of the system.

This Holistic modelling structure will make it possible to set up Digital Twin based on specific Human-Centered concepts. All these new solutions show that it is time to move to a whole new level of Human DT collaboration and to frame this new generation of Digital Twins. According to (Löcklin et al., 2021) the Digital Twin of a human being is the missing piece of the puzzle for the complete implementation of the Digital Twin concept. Here the authors prefer to consider the human as one of the in-

dispensable part of future Digital Twin which will have to be accompanied by new elements to be operational. As a matter of fact, the role of Human in Digital Twin needed to be redefined by considering this new Holistic Framework.

### 3.2 *Autonomy of Human-Machine System*

These new generation of Digital Twin allocate an important value to shared autonomy between human and the twin in order to learn or educate about the allocation of tasks and, in the same time, improving the safety and efficiency of such systems. Therefore, Digital Twin behaves like any automated system and they should include autonomy management processes considering degrees of automation and providing advices to the user. In the new generation of industries, machines are increasingly used to work on hazardous and dynamic environments. In general, machines work with humans in a team. As with HMS, allocation functions must be included to improve Human-Twin cooperation. They are mainly managed by automation levels and structures to decide who is the most competent for a given task, and thus to allocate control to the best.

Among various existing studies, some can be used to develop Human-DT cooperation based on a Holistic design Framework. For example, (Pacaux-Lemoine et al., 2017) defined Human-System cooperation principles applied to Intelligent Manufacturing systems. An assistance system has been designed to help humans when they have to supervise and control an artificial self-organizing manufacturing control system. In the context of sustainable development, there is an importance of holistic designs in intelligent manufacturing systems. Future DT designer need to put forward the need to raise awareness of the risks linked to the great complexity of intelligent manufacturing systems, as well as removing humans from the control loop. Task allocation is predefined according to technical and human factors. However, it is sometimes preferable to assign a task to a human agent, even if it is fully automated, in order to maintain the competence of the operator. A multi-layer decision structure can then be required involving a network of Human-Machine-Twin Systems that share tasks between each parts on strategic, tactical or real-time layer (Vanderhaegen, 2003), (Pacaux-Lemoine et al., 2017). In Vanderhaegen (2003), a Dynamic Task Allocation Structure was proposed. Cooperation between the human operator and the intelligent manufacturing control system is achieved through exchange of information at strategic, tactical, or real-time level. In the strategical layer, a dispatcher's control system will give orders to the dispatcher system present in a tactical layer. Then actions can be realized in real-time on the asset. This configuration distributes dynamically the tasks between the human and the automated system and vary according to the characteristics of the situation and the availability of resources.

Of course, it seems important to characterize the different possible levels of system's autonomy before defining how to allocate the decision to this or that actor. In the literature, there are various Levels of Automation (LoA) defining the interactions between human and an asset in different domains of applications such as advanced manufacturing,

robotics, aeronautics, car or train driving. Several classifications describe LoA as the degrees for which tasks are automated, from fully manual to fully automated. Adjusting LoA should allow improving the overall HMS Twin performance. The approach described by Habib et al. (2017) uses Human-Machine cooperation principles presented in order to assess a maximum of interactions between human and machine. Designing Levels of Automation would provide policies in order to manage the function allocation and the authority allocation between human and machine. These LoA and rules can be implemented when designing Holistic Digital Twin. This method underlines all the steps that must be followed in order to anticipate any problem that can occur when operator cooperates with a new intelligent system. Such structures should improve the autonomy and plasticity characteristics of a Digital Twin.

Considering and studying different degrees of automation to make system resilient to various threats and risks is mandatory in this new industry revolution (Brandenburger and Naumann, 2019). This requires the study of different Human-Machine characteristic like skill, availability and possibilities to interact for shared control (Vanderhaegen, 1999), (Vanderhaegen, 2021a) and different Human-Machine abilities like abilities to cooperate, compete, learn or educate (Vanderhaegen, 2012), (Vanderhaegen, 2021b). This requires also paying particular attention when designing the whole system so that humans can give their very best, especially when no technical solution is available. Such techniques should be adapted for a Digital Twin integration.

### 3.3 *Environment of Human-Machine System*

In the defined Holistic Framework for HMS Digital Twin, decision can be achieved only if the context of the process and the situation of the operator in it are both well known. The environment of the Human-Machine Systems is an important element in its DT design. Indeed, thanks to the interest in Digital Twins, a new concept of Augmented Digital Twin emerged. Wei (2021) proposed a new notion in medicine for Digital Twins of human bodies and their interactions. Besides physical and digital parts from Grieves, environment is taken into account. Other entities are added to the physical space and other Digital Twins corresponding to these new entities are added to the cyberspace. In this architecture, smart handheld devices, mobile phones, hospitals or other institutes are present and get information which is transferred and updated consecutively into cyberspace. The model analyses point-in-time data, historical data, and extracts information from this data. It then provides feedback from the data to the user, such as diagnostics, predictions or other suggestions. This concept is interesting and it should inspire future Digital Twin design more centered on humans. The Holistic Framework considered that multiple entities architecture, that is why the DT is split into several parts: one for the Machine, a second one for the whole Human Operator skills and its knowledge, and finally as many models as there are entities or group of entities. In order to function, the various elements, assets and humans must communicate with each other to obtain a common network of systems. To this, must be added additional technologies that allow the capture of contextual information about the machine

(consumption, temperature, speed, or modes of operation) as well as information about the operator, such as his/her tasks and work objectives.

Next elements are specific devices for data acquisition example in a Holistic DT. Unlike a process or a machine, data that characterizes it are not easily accessible. With an asset, most of the information is digital and the connection to the Digital Twin is now relatively simple. However, when it comes to collect data on a living being, this becomes more complex. Data acquisition devices are used to collect (automatically if possible) a wide variety of data in order to prevent human action or reaction and possible accidents. Indeed, accidents are due to multiple combinations of various technical, organizational, human and contextual factors (Vanderhaegen et al., 2021). This is why devices such as eye-tracker, heartbeat recorder and camera can be configured to establish principles of vigilance detection or emotional recognition. Indeed, as time goes, new situations and behaviors that could not be predicted are appearing. Such technologies can be efficient ways to achieve a complete and well-designed Digital Twin taking into account each aspect of the environment and the user surroundings. There are several case studies and proven applications where these technologies have been applied to capture human-related information. Eye-tracking concept is useful in order to record eye activities on specific area during an experiment duration (Vanderhaegen et al., 2020). Heart signals can be collected to diagnose impacts of the synchronization between heartbeats and dynamic events (Vanderhaegen et al., 2020). Finally, human emotion and attention can be analyzed thanks to audio-visual and heart signals (Bendjoudi et al., 2020). Such new design and associated communications will help to describe systems as multi-agents more comprehensively. The physical and social context in which the controller or human acts is very important. Environmental factors, circumstances or surroundings have greater influence to human beings than on machines.

### 3.4 User of Human-Machine System

Operator in Industry 4.0 (Operator 4.0) is a smart and skilled operator who performs cooperative work with machines. For Operator 4.0 who have to interact with Digital Twins, designers need to do so in a way that is simple and intuitive for them to visualize twins' models and explore relationship between different assets, people, and processes of the system. Historically, the Digital Twin user only interacts with a screen and a keyboard, he/she is in some ways still too distant from the system. Development of future generation of Digital Twins will be based on Operator 4.0 concepts related to cognitive, sensory or physical interaction devices.

One of the challenges of a Digital Twin based on Holistic concept is to improve user integration, collaboration and inclusion with the twin. Beyond 2D and 3D representations there are new concept of Augmented Reality (AR), Virtual Reality (VR) or even hybrid concept as Mixed Reality (MR). Augmented Reality (AR) enriching the real-world environment with digital information and media, in other words, the visible world is overlaid with a layer of digital content (sound, video, graphics, etc.). AR can be consid-

ered as an enabling technology (head-gear, smart-phones, AR projectors, etc.) for improving the transfer of information of the human from the digital to the physical world in a non-intrusive way. It is possible to imagine linking these devices to the Digital Twin to provide prediction or other information on the system directly in the user's line of sight. In addition to all the benefits of a DT, the combination will simplify Human-Machine and Human-Twin interactions and allow quick response to urgent situations. Another way for immersing Digital Twin user in the work process environment is the use of Virtual Reality (VR). In contrast to Augmented Reality, VR creates a real or imaginary environment computer-generated, whereas AR adds virtual elements to a real environment. Thus, Virtual Reality entirely occludes the user's natural surroundings. It artificially reproduces a sensory experience, which can include sight, touch, hearing or even smell. Some devices enable that technology, like virtual reality headset. Finally, the solution could be the Mixed Reality concept, a reality which mix Augmented and Virtual techniques. In this "reality", virtual objects are integrated into the natural world and virtual and real objects coexist that can interact in real time. A virtual object in the environment should response in function to the natural laws and rules of this world (gravity, perspective, etc.). Any change in the real world is reflected in the digital world as well. Further enhancing the user's capabilities is an ultimate goal. These technologies will increase his/her situational awareness. That is therefore interesting to move towards such devices that allow a better immersion of the human in the system environment.

## 4. CONCLUSION

The concept of Digital Twins has existed for more than 50 years, initially for space development purposes, it is now well present in multiple and diverse companies whether for control, diagnosis or optimization. For each need everyone perceives a different solution to their problems and so a different definition of Digital Twin. Interest in DTs is growing faster, and the models are becoming clearer. In order not to be overtaken by this trend, this article also focused on the gaps present in most of Digital Twins design. Firstly, it has been noticed that the existing models do not take into account the autonomy of their systems. A DT may not give good predictions, a shared control device must be put in place, like the one described in this article, to ensure optimal reliability. Autonomy/Plasticity becomes ones of the main emerging characteristics of future systems as Digital Twins to adapt the capabilities of humans and systems regardless of the situations they face (Vanderhaegen, 2017). Secondly, concept of Augmented Digital Twin has been presented in order to clarify the modeling and to take advantage of as many elements as possible that characterize the process or asset. Environmental factors, circumstances and surroundings must be modelled or captured to achieve the most realistic Digital Twin possible. In that way, the final characteristics that have to be improved in DT is the consideration of the user. Indeed, new interfaces are now available and can improve the integration of the user in the whole Human-Machine-Twin System. These three elements added to the classical DT models was capitalized in a Holistic Framework for

Digital Twin. It fills the gaps of some developed models and include each human part in the system. In this way, it is certain that DTs which adopt this Holistic Framework will take into account every aspect of the subject and allow for the design of realistic, efficient and safe Human-Centered Digital Twins. The industry of the future is now within reach with a new generation of Digital Twins.

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