Information Basis of Digital Twins: A Quantifiable Metric for Spatio-Temporal Expressivity

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Abstract: This paper focuses on the concept of Digital Twins and the characterization of Digital Twins in terms of the spatio-temporal extent of the information based on which they operate. Following an in-depth literature review, we observe that even when Digital Twins (and variations of this concept) are qualified in terms of 'levels of information integration', strictly quantifiable metrics are rarely applied. To fill this gap, we propose the term 'information basis', which highlights the quantifiable extent of events occurring in space and time which have an influence on the functionality of the Digital Twin. Following a discussion on the implications of this term, we present an example Digital Twin and discuss how its different alternative implementations would fall on different points of the newly introduced information basis spectrum.

Keywords: Digital Reality; Industry 4.0; Digital Twins; Cyber-Physical Systems; Information Basis

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1 Introduction

Industry 4.0 (I4.0) is an initiative that has appeared in various forms in the past decades. One recent definition in Xu et. al. states that "*Industry 4.0 represents the current trend of automation technologies in the manufacturing industry, and it mainly includes enabling technologies such as the Cyber-Physical Systems (CPS),* *Internet of Things (IoT) and cloud computing*" [1]. According to Germany Trade Invest, Industry 4.0 represents the technological evolution from embedded systems to Cyber-Physical Systems (CPS): "*In Industry 4.0, embedded systems, semantic machine-to-machine communication, IoT and CPS technologies are integrating the virtual space with the physical world, in addition, a new generation of industrial systems, such as smart factories, is emerging to deal with the complexity of production in Cyber-Physical environment*" [2]. Regardless of the context in which the term is used, there is general consensus that digitization is one of the key pillars underlying this initiative. With the rapid growth of digitization and the emergence of Cyber-Physical Systems (CPS), more and more focus is also placed on the concept of Digital Twins (DTs). In the Industry 4.0 era, the virtual copies of the system are able to interact with the physical counterparts in a bi-directional way, and are capable of replicating and analyzing production systems in real-time. [3]

In this paper, we provide an overview of the use cases underlying DTs, as well as of the various concepts based on which DTs have been commonly described in the scientific and professional literature (Section 2). Based on this short survey, we argue that one aspect in particular – the idea of spatial and temporal scope represented by a DT – is underrepresented in the literature. To compensate for this gap, we propose the concept of 'information basis' of Digital Twins, to highlight the quantifiable extent of events occurring in space and time which have an influence on the functionality of the Digital Twin (Section 3). Finally, we briefly present a digital twin developed in our lab and provide a discussion on how the concept of information basis is relevant to this particular example (Section 4).

2 History, Use Cases and Nomenclature of DTs

One of the first formulations of Digital Twins (DTs) was proposed in 2005 by M.W. Grieves, in the context of his 'Mirrored Space Model' [4], based upon which NASA began to use the term Digital Twin in 2010: "*A digital twin is an integrated multiphysics, multiscale simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin.*" [5]. Many works have built on and expanded upon this concept, up until the most recent past, e.g. [6, 3, 7].

2.1 Categorization of Digital Twins in Terms of Use Case

With the evolution of science and industry, the concept of DTs is no longer restricted to aviation and has made its way into many fields. In the field of production engineering, a common goal today is to apply digital twins toward the creation of intelligent production environments which can make use of novel technologies and novel capabilities, including those of simulation and data-driven adaptability/learning. The role of Digital Twins in this context can be broken into 3 main categories [8]:

1. Digital Twins for monitoring: whether to achieve more detailed analyses, or to support better design and maintenance processes. Examples include monitoring anomalies, fatigue, crack paths or in the physical twin [9, 10, 11, 12, 13, 14, 15]; Monitoring geometric and plastic deformations in the material composition of the physical twin [16]; Modeling reliability of the physical system [17].
2. Digital twins for lifecycle mirroring: such that the target of digital mirroring is the lifecycle of the physical system. Examples include monitoring of the long-term behavior of the system and predicting its performances by taking into account the different synergistic effects of environmental conditions [15, 18, 19, 20]; providing information continuity along the different phases of the lifecycle [21, 22]; virtual commissioning of the system [23, 24]; managing the lifecycle of Internet of Things devices [25].
3. Digital Twins for Decision Making: here, the goal is to support engineering and statistical analyses in the context of the production system. Examples include optimization of system behaviour during design phase [26, 27, 22, 28, 29]; Optimization of product lifecycle, i.e. knowing the past and present states, it is possible to predict and optimize the future performances [30, 24].

It follows from the above that existing strategies for the use of DTs naturally support the operation of the physical system being modeled. This claim is well supported by a recent survey by Liu et. al. , in which these use cases were also complemented by a quantitative assessment of their relative weight in the academic literature [31]. Thus, the authors identified the topics of Concept, Technology, Paradigm / Framework and Application, and went on to show that the prevalence of Application type contributions outweighed all three other topics combined. Further, the authors also qualified existing DT solutions based on the length of their lifecycle, within the categories of Design, Manufacturing, Service, Retirement and Full Lifecycle. The conclusion of this latter analysis was that most DT solutions focus on only a single phase of the lifecycle and only a mere 5% of solutions focus on the entire lifecycle. The most common scope of DTs was in Manufacturing and Service.

2.2 Categorization of Digital Twins in Terms of Directionality of Communication

In their paper published in 2018, Kitzinger et. al. propose to categorize DTs as belonging to one of three categories based especially on the type of communication between the physical and digital components of the DT:

- Digital Model: "A Digital Model is a digital representation of an existing or planned physical object that does not use any form of automated data exchange between the physical object and the digital object" [32].
- Digital Shadow: "If there further exists an automated one-way data flow between the state of an existing physical object and a digital object, one might refer to such a combination as Digital Shadow. A change in state of the physical object leads to a change of state in the digital object, but not vice versa" [32].
- Digital Twin: "The data flows between an existing physical object and a digital object are fully integrated in both directions, one might refer to it as Digital Twin. In such a combination, the digital object might also act as controlling instance of the physical object. A change in state of the physical object directly leads to a change in state of the digital object and vice versa" [32].

Based on the literature, it can be concluded that most integrations are being developed at the lower levels (DM, DS), and that the higher-level DTs (at least within this nomenclature) mostly appear at a conceptual level and not at the level of real use-cases [32].

In the survey mentioned earlier, Liu et. al. also uses these same levels of integration based on the communication between physical and digital parts of the given system [31]. However, while this nomenclature is perfectly valid in case of Cyber-Physical Production Systems (CPPS), it is not necessarily complete when it comes to the characterization of DTs. Thus, in the paper, Liu et. al. define Digital Twins based on a further, more detailed set of characteristics:

- Individualized: "This means that digital twin is in a one-to-one relationship with the individual physical twin. In other words, digital twin is as designed, as manufactured, as used, as maintained as the physical twin" [31].
- High-fidelity: "This means that digital twin can simulate the physical twin's behavior in the virtual space as exactly as possible, which requires multi physics modeling and continuous model updating through the whole lifecycle" [31].
- Real-time: "This means that digital twin responds to its physical twin with relatively low latency, which is made possible by recent advances in mobile communication and IoT technologies" [31].
- Controllable: "This means that changes to the digital twin or to the physical twin controls the other twin. This is the last step that closes the loop between digital and physical twins and realizes digital-physical convergence" [31].

According to Madni et. al., digital twins can be used both in the context of automated and manual processes in production engineering. Data relevant to the state of the processes, including performance, maintenance and health data can be collected and then synchronized with the digital twin. Because of this generality in applicability, and also due to the fact that practitioners often view any kind of digitized version of a physical system as a digital twin, Madni et. al. define four levels of virtual representation – each with its own purpose and scope in the underlying system's lifecycle [33]:

1. Pre-Digital Twin: Virtual system model with emphasis on technology and technical risk mitigation. Physical Twin does not exist. Data Acquisition from Physical Twin not applicable [33].
2. Digital Twin: Virtual system model of the physical twin. Physical Twin does exist. Data Acquisition from Physical Twin applicable, batch updates [33].
3. Adaptive Digital Twin: Virtual system model of the physical twin with adaptive UI. Physical Twin does exist. Data Acquisition from Physical Twin applicable, real-time updates. Machine Learning (Operator Preferences) [33].
4. Intelligent Digital Twin: Virtual system model of the physical twin with adaptive UI and reinforcement learning. Physical Twin does exist. Data Acquisition from Physical Twin is applicable, with batch / real-time updates. Machine Learning (Operator Preferences and System / Environment) [33].

In a broad sense, this categorization is similar to the previously introduced ones in that first and foremost it emphasizes the link between the physical and digital systems which form the twin. However, one novel aspect here is the appearance of machine learning, which brings Madhi et. al. 's conception of DTs closer to the question of what can be achieved using DTs, rather than how the communication is implemented. In this way, prognostications of future states become possible based on past states of the DT.

Nevertheless, we can see that one of the most salient features of DTs in in the literature seems to be the form of communication between the physical and digital components. In a recent survey of industrial applications of DTs, Negri et. al. also places a strong emphasis on this question, in the sense that the work highlights the ability of DTs to both monitoring and optimization services (the latter based on remote actuation). More generally, the many works in the literature emphasize both directions of communication; even as uni-directional communication still remains the norm in most real-world applications [32, 3]. One recent exception is an application presented by Bambura et. al. in 2020 [34]. At the same time, both Bambura et. al. and Redelinghuys et. al. have highlighted the problem of communciation latency, which is especially problematic in the case of bi-directional (closed-loop) communication, causing such DTs to be aptly characterized as close to real-time systems [34, 35].

2.3 Object-Oriented Digital Twins, Process-Oriented Digital Twins and Their Simulation Capabilities

Based on the categorization of DTs, from different nature of use and varying integration levels, the methods needed for the implementation differs greatly. The implementation and referred methods include, but are not limited to simulation (e.g. DES) methods, communication protocols, and core IT technologies in Industry 4.0 [32].

Due to the strong link between DTs and the notion of simulation, it may be worth investigation DTs from this perspective as well. In particular, there may be value in distinguishing between "object-oriented" and "process-oriented" DTs. Relevance to simulation is especially clear in the case of process-oriented DTs, and such DTs can be further qualified based on the following considerations – according to Negri et. al. [8]:

1. Some works consider DTs as representing systems based on which it is possible to create simulations, e.g. [10, 11, 12, 13, 14, 17, 21, 23, 24, 27, 36, 28, 29, 37]

2. Other works consider DTs as a simulation of the underlying system in and of themselves, e.g. [5, 9, 18, 26, 38, 39]

Using (offline) simulation, the performance of a physical system can be compared to the data (expected performance) produced by the digital twin, enabling decisions to be made that better support future interventions or developments to the system. By repeatedly updating the data in the digital twin based on measurements on the physical system, engineers can improve the digital models of the system, leading to both more precise analyses (i.e. recommendations on how to improve the performance of the physical system based on offline computations); as well as to the bootstrapping of further, more precise, even real-time simulation-based predictions on its future states and performance [33]. A possible next step in this evolution is the use of *proactive simulations*, which not only predict future states in real-time, but also carry out automated interventions to keep the physical system within the boundaries of some desired set of states.

Several recent works have highlighted this simulation-oriented aspect of DTs [35]. Schluse and Rossmann proposed the concept of "Experimentable Digital Twins" to highlight the role of simulation in DTs and its application toward the simplification of processes [40]. In all cases, simulations are viable when communication is bi-directional / closed-loop [31, 41].

3 Information Basis of Digital Twins

Based on the literature review in the previous section, we can make several claims.

First, it seems that in some cases the different levels of functionality and integration cannot be separated in a conceptually clear-cut way, due to a lack of quantifiable metrics. For example, the distinction between DTs, Adaptive DTs and Intelligent DTs is mostly a question of degree rather than a matter of clear distinction. Other aspects often highlighted in the literature, such as the notion of high-fidelity or real-time representations can be equally elusive.

In our own analyses, the nomenclature of directionality of communication (levels of integration) still seems viable. Thus, in accordance with the literature, we distinguish between the 3 levels of integration shown in Table 1 and make the claim that in order for a digital representation to be considered as a Digital Twin, there must be an existing physical system that engages in a bi-directional communication with the digital representation and that can thus be controlled by users or other systems via this digital representation.

Table 1
Levels of integration corresponding to DTs and other related concepts (DM and DS). The three levels can be clearly differentiated based on the existence of a physical counterpart and affordance for remote control.

	Physical System	**Data Communication**	**Control**	**Purpose of Model**
Digital Model	-	-	-	design tool
Digital Shadow	exists	uni-directional	-	virtual model of system
Digital Twin	exists	bi-directional	possible	virtual model of system

At the same time, the dimension of integration level leaves aside the question of how detailed a DT is in its representational and communicational capabilities. To address this question, we introduce the notion of '***information basis***', which expresses the *quantifiable extent of events occurring in space and time which have an influence on the functionality of the Digital Twin*.

Table 2
Dimensions of information basis

Spatial	Possibility of virtual augmentation	no	optionally	yes
	Number of source devices	1-5	6-49	50+
	Number of locations for intervention	1	2-5	5+
Temporal	Period of state changes on the source device [s]	0-1	1-60	60+
	Period of physical-to-digital updates [s]	0-1	1-60	60+

The interpretation of this concept is further explained in Table 2.

The spatial dimension of the information basis concept is parameterized on the one hand by the number of devices providing information to the DT, when considering the level of signal sources (rather than higher-level interfaces) as the underlying reality for counting number of devices. At first, based on practical considerations, we might distinguish between 3 categories of spatial information basis in this dimension, ranging from small-sized (1-5 source devices), medium-sized (6-49 source devices) and large-sized (50+ source devices) information bases. It can be conjectured that the larger this number, the more complex the system will be, and the higher degree of automation it will represent. This latter aspect is especially important in the creation and analysis of DTs.

At the same time, another component of the spatial dimension of information basis is the question of how many “locations” are provided by a DT where external interventions are possible. If there is at least one such location, then it is already reasonable to consider the system as a DT. Also, the more locations are provided for such interventions, it can be expected that the closer the interoperability will be between the physical and digital components of the DT. Being able to answer the question of how easily the system model of the physical system can be virtualized is part and parcel of gaining an understanding of the depth of a DT.

The temporal dimension of the information basis concept, in turn, is characterized via the period (inverse frequency) of state changes in the physical component, and the period (inverse frequency) of information transfer between the physical and digital component of the DT. The specific period values of state changes will in general depend, to a large extent, on the use-case scenario for the physical system; hence, we propose to distinguish between DTs in which the temporal information basis is less than 1 second, between 1 and 60 seconds, and over 60 seconds. With respect to the period of information transfer, it is also possible to distinguish between DTs in which the physical and digital components exchange information at a close-to-real-time frequency, or at rate of seconds, hours or even days. Note that true real-time communication is impossible in a physical sense, but from an IT perspective, nanosecond-level frequencies can be regarded as real-time, whereas in the case of DTs in production engineering environments, the nominal update frequency of the communication devices used is specified at the level of milliseconds. At the same time, updates provided at a scale of milliseconds are generally perfectly suitable to practical applications and do not adversely affect the usefulness of DTs.

In addition to the above clusterizaton along the different dimensions of information basis, it can be further remarked that the two parameters considered within the temporal dimension are not completely independent and can have a decisive influence on the quality of the DT. Specifically, the frequency of state changes within the physical component can be as high as any frequency; that is, if the frequency of communication is lower, a large number of intervening physical events will remain unreported between any two communication events, which can lead to increased uncertainty as to whether the DT can reflect the underlying process with reasonable fidelity. As a result, we can make the claim that:

1. If the rate of information transfer is higher than the rate of physical state change, the DT can be considered as a **real-time-updated DT** (note that here, ‘real-time’ refers not to the technical capabilities of the components of the DT, but rather reflects the temporal communication between the components);
2. If conversely the rate of information transfer is lower than the rate of physical state change, the DT can be considered as a **batch-updated DT**

Thus, the ideal information transmission frequency seems to be the minimal frequency at which all state changes within the system can be communicated to the DT, as it is guaranteed that all state changes can be processed and reflected in the digital representation. Real-time-updated DTs, in turn, hold further potential for deeper inquiry using machine learning, predictive forecasting, carrying out proactive interventions etc.

4 Use-Case Example: Development of a Digital Twin

The Cyber-Physical Production Systems Lab at Széchenyi István University (SZE) is equipped with an automated FESTO didactic production line (ProLog factory), as shown in Figure 1. The production line is characterized by a linear material flow, and automated work stations with various functionalities. Capabilities include loading, form and color based separation, vacuum pick-and-place as well as other processing capabilities; and the system also includes fluid muscle stations, storing stations and commissioning stations - using purely electrical, pneumatic or in some cases electropneumatic actuators as well as inductive, capacitive or color sensors). The work stations are equipped with individual controllers, therefore they are fully operational even as separate entities. User interventions are made possible via modern Human-Machine Interfaces.

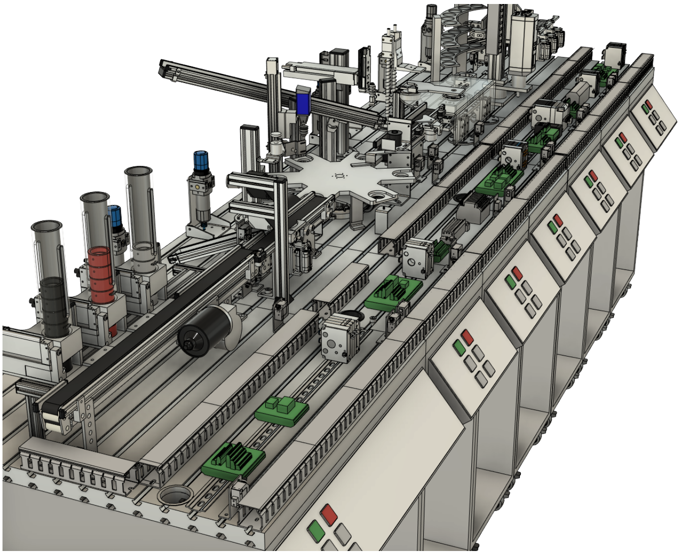

Figure 1
FESTO ProLog factory 3D model

Given the high level of automation provided by this system, it is amenable to the creation of an accompanying digital twin. The most important requirements in this context are:

- Communication protocol should be based on the OPC-UA standard
- The rate of communication should be close to real time
- Communication between physical and digital components is required to be bi-directional
- The DT should be capable of simulation using Discrete Event Simulation (DES) techniques
- The physical process should operate based on decisions made at the level of the DT (true DT intervention).

4.1 System Components and Architecture

The most important part of this development was the communication between the physical and digital comopnents, in terms of quality and speed.

The OPC-UA protocol is a platform-independent and unified standard that enables services to be modelled, connected to and exposed at a high level, without any restrictions on the domain and the way in which its key data types are modeled [42].

From the perspective of the Cyber-Physical System to be created, it was important to ensure that all components are compatible with OPC-UA. The control and external communication of the production line was implemented via an S7-1500 PLC, which supports the OPC-UA protocol as is. The DT, in turn, was implemented via the Siemens Tecnomatix Plant Simulation, which is an object-oriented, discrete event driven process simulation platform. The topology of the physical system (Figure 2) is such that the main control unit has a serial connection to the DT.

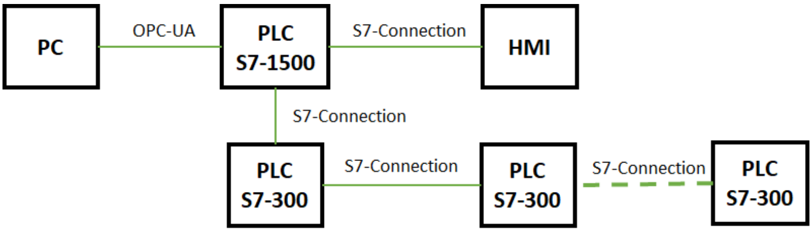

Figure 2
CPS topology

A key property of communication system is that there is a hierarchical (i.e., sender -receiver) relationship between the communicating units. Here in this case, too, the OPC-UA protocol is based on a client-server relationship. In the developed system, the control PLC on the physical side represents the server side, and the DT – i.e. the Plant Simulation software is the client (Table 3).

Table 3
Physical- Digital layer comparison

	Physical layer	**Digital layer**
Hardware	FESTO prolog Factory	PC
Software	TIA Portal	Plant Simulation
OPC-UA	Server	Client

When designing the communication, it was also necessary to create an OPC UA information model. The information model is part of the protocol, the methods and variables defined here perform a continuous data exchange during the server-client connection; a condition for the operation of the digital twin. The information model that can be integrated into the controller was created using the Siemens

SiOME software.

Another important requirement for the developed system was the implementation of close-to-real-time communication. On the server side, the minimum publishing interval was 200 ms, which meant that the DT would be a batch-updated DT. In other words, all previously selected parameters are transmitted at this frequency, regardless of whether their value has changed in the given update cycle. These parameters can be sensor values from the physical system, actuator states, or memory values in the control unit (PLC).

In the Plant Simulation platform, the minimum server read interval on the client side is 1 ms (Read interval). Functionally, this means that the received values are transmitted to the objects after this time, regardless of whether there has been a change (The OPC UA object transmits changed values to Plant Simulation after this time has elapsed.). The read interval is smaller than the server-side send interval, but it does not cause a functional difference; it would be a problem only if the set minimum read interval was greater than the server send interval. However, in our case, two-way communication was also possible, with the minimum server write interval being 10 ms (the rate at which Plant Simulation transmits the values to the OPC server).

Based on the minimum values specified for the server-client connection, it can be concluded that it was not possible to achieve real-time communication, however, near-real-time communication was possible and at a rate that is perfectly suitable in the case of automated production lines.

4.2 Cyber-Physical Processes

The goal of the process-level approach behind the Cyber-Physical System was to ensure that the decisions made in the digital twin could lead to real interventions in the physical system. In the case of a process, an important aspect is in which sub-processes and decision points it is possible to allow external interventions. The possibility of intervening in a process is also available at the security and technical level. The safety approach mainly reflects occupational safety aspects, as the personnel cannot be prepared to make interventions when the system is running in a mode outside of its usual operation at a random time, so the risk of an accident is higher. An important question is whether equipment operating in such a mode can be considered as collaborative workspace equipment and thus subject to collaborative regulation. Another important aspect of intervening in the system can be interpreted at the technical level. In the case of processes that do not operate completely manually, the sensor and control technology is already appearing, the control systems are characterized by the fact that they perform pre-written processes based on the signals coming from the system. In practice, this means that at any point where we intervene in the system, a signal, a state, changes, to which state the control system triggers a predefined response.

Table 4
WS 4 processes

Step	Process
1.	The conveyor belt is started.
2.	The product arrives at the work station.
3.	A stopwatch is triggered at the work location.
4.	The product arrives at the work location.
5.	The conveyor belt stops.
6.	The manipulator moves to pick up the part that is to be installed, the vacuum becomes active.
7.	The part is picked up (if the part is unavailable, the manipulator waits).
8.	The manipulator transports the part into the installation position, the vacuum becomes inactive.
9.	The manipulator returns to its default pose, the stopwatch at the work location becomes inactive.
10.	The conveyor belt starts.
11.	The product leaves the workstation.

However, the intervention may not have been the cause of the reaction, it was just a consequence. Unwanted intervention can result in tool breakage, control error and can interrupt the entire process. Therefore, it is very important to define where, how and for what purpose we intervene in the processes of the physical system.

On the automatic production line affected by the development, the material flow is linear, mainly in the technological and logistical processes, while the built-in part comes from a separate branch. For the vacuum manipulator on the fourth workstation (WS 4), the arrival and storage of the inserted part is implemented by means of a gravity slider. In terms of process, component supply results in an external dependency state, so this is a potential intervention point for DTs. On the fourth workstation (WS 4), the logical sequence of the processes (Table 4) that are predefined and loaded into the PLC (and cannot be changed without a restart) are as follows:

From the point of view of the process, WS 4, Step 7 depends on the condition of the presence of the part. This logical condition is a suitable place for external interventions by the DT, independent of any actuator and sensor, which can be achieved simply by assuming the presence of the component as depending on a result which can be obtained only and exclusively from the digital twin (Figure 3). In addition to the need for completeness, it is important to state that any condition or intervention coded in the PLC is suitable for defining additional conditions, but from a practical point of view, the existence of an external intervention / factor can be justified and transparent at this point. The condition can be represented as an employee confirmation or based on a stochastic process, so we can have an effect on the physical system in some defined way, which can be a simple external effect but also an intervention resulting from historical data of internal processes. Thus, the decision made in the digital twin is part of the realization of the physical system.

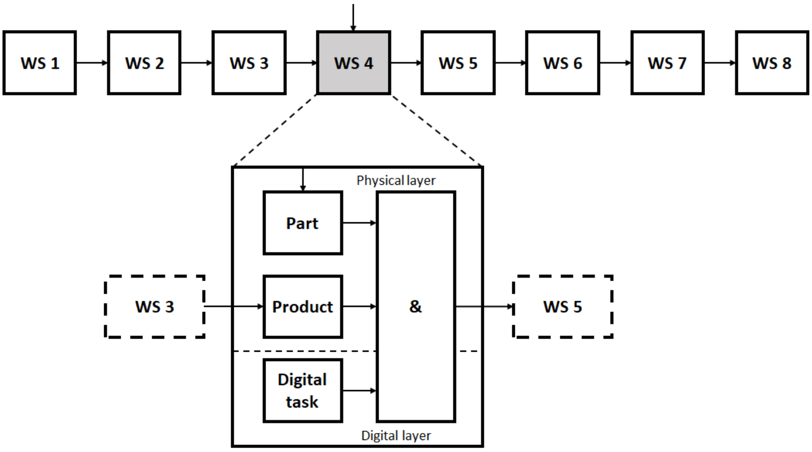

Figure 3
Cyber-physical processes

In the DT, processes operate on the basis of data from a physical process, which are extended with a digital-only task. This task represents a manual operator activity based on stochastic time values in a simulation environment. The digital task starts as a result of Step 7 detailed above, based on parameters from the physical system (Table 5). When the digital task is completed, the conditions in terms of the physical part's availability are met; thus, the required data is transferred to the physical system, and the main process continues with step 8. This method provides the possibility of virtual extension to any physical system, where the virtual extension of the factory and production line in the digital twin is almost limitless in terms of tools and processes.

4.3 Results

As a result of the development, a digital twin with two-way communication based on a close-to-real-time industry standard protocol has been implemented in a simulation environment, where decisions made at the digital level involve real intervention in the physical system. During the development, in line with the preliminary objectives, the most important parameter was to determine the

Table 5
Physical-Digital level processes

Layer	**Process**
Physical	7. Picking up of physical part.
Digital	7.1 Digital task is started.
Digital	7.2 Digital task is finished.
Physical	8. The manipulator transports the part to the installation location.

place, purpose and way of carrying out interventions in the physical system. The other key task was to establish communication, where on the one hand the communication time had to be realized in the close-to-real-time range using a standard protocol, and on the other hand the two-way information transfer required for the intervention had to be ensured. Once the technical conditions for communication have been determined, it was necessary to delimit the data coming from the physical system in order to transmit only the necessary information to the digital twin to avoid unnecessary communication load. The digital twin process took place in a simulation environment, where events occurred based on data from the PLC. In the environment of event-driven process simulation, this required a different model-building logic during model building, because the logic of the material flow in the software was not provided by the digital twin but by the physical system. In the digital twin, a purely digital process was developed to supplement the physical system (Figure 4), the result of which was fed back into the physical system as a function of events.

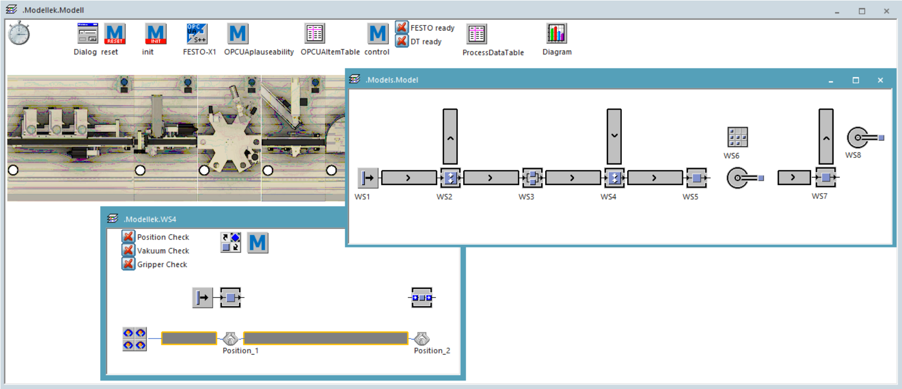

Figure 4
Plant Simulation development environment

The results of this development effort can be evaluated in terms of the scientific literature considered earlier. Based on Kitzinger et. al.'s nomenclature [32], the solution is clearly a Digital Twin. In terms of the integration levels perspective in Liu et. al. [31], the solution is also a Digital Twin, and it can further be characterized by the concepts of individualized, high-fidelity, real-time, controllable DTs. In addition, the solution also fulfills Madni et. al.'s requirements with respect to Digital Twins, but it also is equipped with all the characteristics that are necessary to attain the level of Adaptive and Intelligent DTs. Although the solution does not yet attain this level, the exact status is not a quantifiable metric in any case. In line with the observations in Bambura et. al. and Redelinghuys et. al. [34, 35], it can be shown that the developed system does not achieve real-time communication, but it nevertheless implements close-to-real-time communication. Liu et. al. and Bambura et. al. [31, 34] do emphasize the importance of bi-directional communication, whieh was implemented as part of the solution. When it comes to simulation-based DTs, there are several accepted examples of this concept in the literature, in all cases based on a bi-directional close-to-real-time communication similar to the solution developed here [40, 41]. Based on all of these considerations, the developed solution was a successful implementation of a DT with great potential. It is also characterized by the possibility of carrying out interventions in the physical system using the DT, which is uncommon in the relevant literature.

Based on the notion of information basis, relevant spatial and temporal properties can be used to evaluate the quality and the depth of the developed DT. In analyzing the spatial qualities of the system, it is clear that the virtual augmentation of the system is possible, because the system architecture and the used software support it. The number of source devices is 50+, which includes sensors, actuators, drives, manipulators and robots. The number of locations for intervention has already reached 2 during the development process. Based on the temporal dimension of the information basis, the period of state changes within the source device is between 1 and 60 seconds. The period of physical-to-digital updates is less than 1 second. Thus, it can be said that the rate of information transfer is higher than the rate of physical state change, so the developed DT can be considered as a real-time-updated DT.

Conclusions

With the spread of the I4.0 concept and the appearance of CPS, the need for Digital Twins (DTs) is becoming more and more obvious. In recent years, many theoretical and practical examples of DTs have become known, which typically use and interpret DTs in different contexts. In this paper, we provided an overview of the use cases underlying DTs, as well as of the various concepts based on which DTs have been commonly described in the scientific and professional literature.

As a result of the review, it can be said that there is no uniform interpretation and comparison method. We showed that existing nomenclatures have significant overlaps but are also often difficult to quantify, which led to our motivation to propose the concept of information basis: a quantifiable multi-dimensional metric that expresses the extent of the spatial and temporal domain that has an influence on the behavior of a DT.

In the latter part of the paper, we described a motivating example which was physically and digitally implemented in a laboratory environment.

In a practical example, the close-to-real-time bi-directional connection of the physical system with the DT was implemented, and as a result of the decisions made in the cyber space, the physical process could operate seamlessly, and it was shown to adhere to all major requirements with respect to Digital Twins.

Acknowledgements

Project no. TKP2021-NKTA-48 has been implemented with the support provided by the Ministry of Innovation and Technology of Hungary from the National Research, Development and Innovation Fund, financed under the TKP2021-NKTA funding scheme.

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