A Six-Layer Digital Twin Architecture for a Manufacturing Cell: Proceedings of SOHOMA 2018

Chapter · January 2019

DOI: 10.1007/978-3-030-03003-2_32

3 authors:

Anro Johannes Hermanus Redelinghuys
Stellenbosch University

Anton Herman Basson
Stellenbosch University

Karel Kruger
Stellenbosch University

in Service Orientation in Holonic and Multi-Agent Manufacturing, Proceedings of SOHOMA 2018, Studies in Computational Intelligence, Volume 803, pp 412-423

A Six-Layer Digital Twin Architecture for a Manufacturing Cell

AJH Redelinghuys, AH Basson, K Kruger

Department of Mechanical and Mechatronic Engineering, University of Stellenbosch, Stellenbosch, 7600, South Africa
{ajhr, ahb, kkruger}@sun.ac.za

Abstract. Industrie 4.0, cyber-physical production systems (CPPS) and the Internet of Things (IoT) are current focusses in automation and data exchange in manufacturing, arising from the rapid increase in capabilities in information and communication technologies (ICTs) and the ubiquitous internet. A key enabler for the advances promised by CPPSs is the concept of a "digital twin", which is the cyber representation of the physical twin, which in this paper is a manufacturing cell. This paper presents an architecture for such a digital twin, that enables exchanging data and information between a remote emulation or simulation and the physical twin. The architecture comprises different layers, including a local data layer, an IoT Gateway layer, cloud-based databases and a layer containing emulations and simulations.

Keywords: Industrie 4.0 · Cyber Physical Systems (CPS) · Internet of Things (IoT) · Digital Twin · OPC · Tecnomatix

1 Introduction

The German industry's vision to be integrated with the Industrie 4.0 principles by 2020 has raised a lot of attention in the research and development community. Industrie 4.0 is focused on creating a smart, networked world with smart products, procedures and processes. The potential of the Industrie 4.0 initiative includes [1] meeting individual customer requirements, flexibility, optimized decision-making, resource productivity and efficiency and creating value opportunities through new services.

Cyber-physical production systems (CPPSs), a subset of cyber-physical systems (CPSs), overlap with Industrie 4.0 and includes the further development and integration of computer science, information and communication technology, and manufacturing science and technology [1, 2].

CPPSs consist of autonomous and cooperative elements and sub-systems that are interconnected across all levels of the automation hierarchy. **Fig. 1** illustrates the transformation from an automation hierarchy to CPS-based automation. The typical field and control levels, which include PLCs, still exist, while the higher levels in the automation hierarchy are characterized with a more decentralized way of functioning. CPS-based automation emphasizes the connectedness between the higher levels of the automation hierarchy [2].

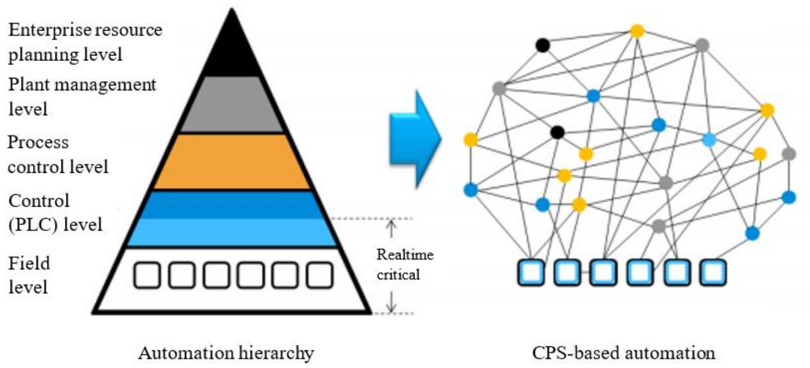

Fig. 1. Decomposition of the automation hierarchy with distributed services (adapted from [3])

The expectations of CPSs and CPPSs include [2, 4]:

- Robustness at every level
- Self-organization, self-maintenance, self-repair, etc.
- Safety
- Remote diagnosis
- Real-time control
- Autonomous navigation
- Transparency
- Predictability
- Efficiency

A key enabler for the advances promised by CPPSs and Industrie 4.0 is the concept of a digital twin, which is the cyber representation of a physical twin. This paper focusses on a digital twin for a manufacturing cell, the physical twin in this paper, where the digital twin enables exchanging data and information between cyberspace and the physical twin.

The paper presents a six-layer architecture for such a digital twin. In the next section, the role of a digital twin is explored, followed in Section 3 with a consideration of OPC UA, i.e. Open Platform Communications (Unified Architecture), in the context of Industrie 4.0. OPC UA is here considered to be a key enabler. Section 4 presents the digital twin architecture proposed here for manufacturing cells, while its evaluation is considered in Section 5. Finally, a discussion and conclusion are presented.

2 The Digital Twin

According to a NASA report [5], a digital twin is "an integrated multi-physics, multiscale, probabilistic simulation of a system that uses the best available physical models, sensor updates, fleet history, etc. to mirror the life of its flying twin". Forbes [6] mentioned that a digital twin trends at number five in “Gartner's Top 10 Strategic

Technology Trends For 2017" and that a digital twin can be used to analyze and simulate real world conditions, respond to changes, improve operations and add value.

A virtual (or digital) twin, according to [7], is a representation in the cloud of a physical asset or a device. The digital twin's presence in the cloud persists even when its physical counterpart is not always connected, since connectivity can be lost momentarily while it is important for backend software to be able to interrogate the last known status or to control the operating parameters even when the physical twin is not online/connected. The cloud also provides a convenient mechanism for sharing a structured database with other devices of the shop floor and therefore linking the digital twin to its physical twin in a global context. Further, many apps are becoming available to extract value from data in the cloud.

In a manufacturing context, a digital twin is a set of computer models that provide the means to design, validate and optimize a part, a product, a manufacturing process or a production facility in the cyber space. A digital twin enables flexibility in manufacturing by reducing the required time for product design, manufacturing process design, system planning design and production facility design [8]. The evaluation of manufacturing flexibility of a current or proposed production line are made possible with the simulation and testing of the digital twin [9].

Fig. 2 illustrates the connection between the physical world and the cyber world, creating a digital twin of the physical production system. A CPPS consist of three main parts (adapted from [10]):

- The physical system in real space (physical twin),
- The virtual system in cyberspace (digital twin),
- The connection between the cyber space and real space for transferring data and information using the IoT.

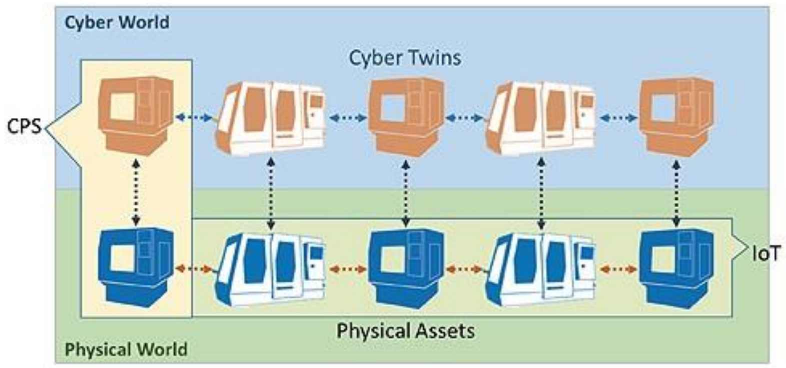

Fig. 2. The physical production system in cyberspace presented as a digital twin [11]

The combination of the physical production system and its corresponding digital twin, are the fundamental building blocks of fully connected and flexible systems that are able to learn and adapt to new demands. Ideas about the value and role of the digital twin are still developing at this stage. Some of the roles postulated in recent literature are [12] [13] [8] [7]:

- Remote monitoring – The digital twin allows remote visibility of the operations of large interconnected systems, such as manufacturing systems, which allows virtual monitoring systems and validation of the current status of production systems (i.e. energy monitoring and fault monitoring).
- Predictive analytics – Prediction of the future state of the physical twin can be used to predict errors and problems in manufacturing facilities before they occur, therefore preventing downtime, failures and more.
- Simulating future behavior – The digital twin can be used, by virtually simulating manufacturing processes, to plan for the future, reconfiguration of processes and the system in response to external changes.
- Optimization and validation - Validate and optimize the system's operation using simulation and real-time sensor feedback (i.e. batch mix optimization).
- Documentation and communication - The digital twin provides a mechanism to understand and explain behaviors, and can be used as communication and documentation mechanism to understand the behavior of equipment.
- Connection of disparate systems such as backend business applications – The digital twin can be used to connect to with backend business applications to achieve business outcomes in the context of supply chain operations.
- Global Digital Twin Control – Planning the batch, such as establishing the order in which physical twins are introduced in the manufacturing environment, scheduling product operations and allocating resources to operations.

3 Industrie 4.0 and OPC UA

According to a major vendor of industrial communication solutions [14], modern industrial user demands include:

- Global connectivity – across a shop-floor or across the world.
- Integration and interoperability – between production, non-production, business and IT systems.
- Data security and integrity at every level.
- Real time performance and reliability.
- Centralization, simplification and standardization.
- Business continuity, through diagnostics, redundancy and recovery capabilities.

OPC UA provides many of these requirements. In manufacturing and automation, OPC UA is striving towards the international standard for horizontal and vertical communication, providing semantic interoperability for the world of connected systems. OPC UA therefore provides the foundation for connectivity for the Internet of Things (IoT) and for the Industrie 4.0 [15]. OPC UA forms the bridge between the company management level and embedded automation components or sensors [16].

According to the Global Vice President of the OPC Foundation [17], a main challenge with Industrie 4.0 and the Industrial Internet of Things (IIoT) is the secure data and information exchange between devices, machines and services. He reported that the IEC standard 62541 OLE for Process Control Unified Architecture (OPC UA) was recommended by the Reference Architecture Model for Industrie 4.0 (RAMI 4.0) for implementing the communication layer. He concluded that any product being advertised as “Industrie 4.0 enabled” must be OPC UA-capable. `

Further, [17] states: "*Machine and device manufacturers describe the object-oriented information of their systems and define the access rights along with integrated security features. Germany’s BSI (Bundesamt für Sicherheit in der Informationstechnik, or Federal Office for Information Security) published the results of its security analysis of OPC UA in April 2016 in highly positive terms. This was because machine builders keep full control of the data, i.e. they can distribute it in a targeted and controlled manner, which enables them to participate monetarily in big data applications and data analytics.*" The OPC Foundation [16] claims that the confidentiality of data and information exchange is secured by the encryption of the exchanged messages.

4 Digital Twin Architecture

Fig. 3 illustrates the six-layer digital twin architecture proposed in this paper for a manufacturing cell, with the data/information flows between the layers. The figure illustrates that data/information flows from the physical system or physical twin (Layer 1) to the cloud (Layer 5) where it is stored in an information repository accessible in cyberspace. Information can also flow from the cloud to the physical twin. The architecture, in its fourth layer, has optional data to information conversion functionality. The sixth layer contains simulation or emulation software and other apps that can use the information from the physical twin to realize the expectations of CPPSs, as outlined in Section 1.

The availability and distribution of data, as seen in the figure, contributes to the connectedness paradigm of CPPSs as illustrated in **Fig. 1**.

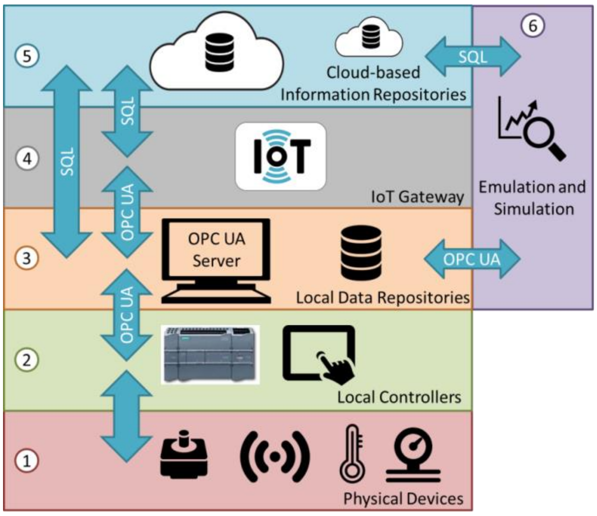

Fig. 3. Connection architecture for a digital twin

4.1 Layers 1 and 2: Physical Twin

The first two layers in **Fig. 3** contain the physical twin. Layer 1 includes various physical devices, such as actuators and sensors, that can provide or consume signals exchanged with the local controller. The local controllers (Layer 2) are considered to be a separate layer since, in addition to their role for the physical twin, they may be used to provide some functionality specific to the digital twin. The ubiquitous controller in manufacturing automation is a programmable logic controller (PLC), but any controller that can interface with Layer 3 will be suitable for this architecture.

4.2 Layer 3: Local Data Repositories

Layer 3 in the architecture contains repositories of data located near the physical twin, such as OPC UA servers (**Fig. 3**) and local databases.

Any vendor-neutral OPC UA server can be set up to exchange data with the physical system. OPC UA servers are able to communicate with many types of devices capable of transmitting and receiving data using OPC UA drivers. Since all major vendors of automation controllers provide interfaces to OPC UA, such a server provides a vendor-neutral interface between the physical twin and cyberspace. Also, OPC UA layer provides other important characteristics described in Section 3, such as security, real time performance, reliability and global connectivity. The expertise required to set up and maintain an OPC UA server is widely available in the manufacturing industry, and entails setting up an OPC UA server, configuring the local controllers in Layer 2 with valid tag names and register values, and setting up the OPC server (Layer 3) to obtain data from Layer 2 using the tags.

In some complex manufacturing cells, the stations (each with their own controller) may share a database to control and synchronize their activities. Such databases can be considered to be part of Layer 3, whether they are created specifically for the digital twin or not.

The data in Layer 3 will reflect the details of the physical twin, but additional processing may be added to Layer 2 specifically to provide data for the sake of the digital twin. However, is likely to be preferable to rather add the functionality required for the digital twin in Layer 4, rather than changing Layer 2, if the physical twin already exists, taking into account the downtime and risks involved in modifying a system in operation. Also, if the digital twin is aimed at a variety of architectures of the physical twin, it is likely to be better to account for the differences in Layer 4.

4.3 Layer 4: IoT Gateway

Layer 4 (**Fig. 3**) acts as gateway between the physical twin and the connected world. This layer provides for the conversion between data in Layer 3 to information in Layer 5, which corresponds to the second function of the 5C architecture for implementing a cyber-physical system [18]. In some situations, the architecture can be simplified by omitting Layer 4, with Layers 3 and 5 directly communicate the data with each other, when the functionality added by the gateway is not required.

Layer 4 is custom developed software that contains an OPC client interfaced with the OPC UA servers on Layer 3, as well as database clients interfacing with the database servers on Layers 3 and 5. Since the IoT Gateway interfaces with both the local and cloud data sources, it is a convenient place to add a graphical user interface (GUI) where some of the digital twin's core operations can be monitored and controlled.

The typical roles of Layer 4, regarding the flow of information from the physical twin to the cyberspace, are:

- Derive information from the data available from Layer 3, such as multi-dimensional data correlation [18] or "data intelligence" where various forms of data are analyzed to make better future decisions [19].
- Select the data to be transmitted to the data repositories to avoid excessive database requirements.
- Pass only the data or information appropriate to each particular data repository in Layer 5 to that repository.
- Prevent bandwidth bottlenecks by limiting the amount of data processed through the network gateway.
- Convert data from a variety of twin architectures into information in a more generic format.

Layer 4 can also play important roles in the flow of information from cyberspace to the physical twin:

- Guard the safety of the physical twin by, for example, ensuring that the physical twin is in an appropriate state before changes commanded from Layer 6, via Layer 5, are transmitted to Layer 3.
- Resolving conflicts in data/information coming from different data repositories on Layer 6, or when changes on Layer 3 and on Layer 6 are incompatible.

For complex manufacturing cells comprising a large number of stations that are complex in their own right, the architecture shown in **Fig. 3** assumes that the stations do not warrant their own digital twins, and that the databases and OPC Servers on Layer 3 provide the data required by the cell-level IoT Gateway. This should be sufficient for the company using the manufacturing cell. However, the company that developed or maintains the manufacturing cell may prefer a hierarchical arrangement, with each station having its own IoT Gateway to enhance the modularity of the digital twins. Then the architecture in **Fig. 3** can be extended so that a cell-level IoT Gateway interfaces with station-level IoT Gateways and not with the normal data sources shown in Layer 3.

4.4 Layer 5: Cloud-based Information Repositories

Layer 5 in **Fig. 3** contains cloud-based database servers that act as information repositories for the information of the physical twin and the digital twin. The information will typically record the history of the physical twin and the current/latest available state of the physical, with acknowledged latencies.

Multiple repositories are envisaged since different stake-holders are likely to have different information needs and access rights to the information. For example, the developer of the physical twin may require access to critical performance parameters, but may want to control access to that information, while the manufacturing plant may require that quality assurance information is stored, but would want to keep that information confidential.

Hosting these repositories in the cloud enhances the availability, accessibility and connectedness of the digital twin. The specialized expertise required to manage such a database server, taking into account scalability, reliability and security, is usually not available in manufacturing enterprises. Some automation vendors are reported to be developing such cloud-based repositories, but similar services are already available from a variety of other sources.

4.5 Layer 6: Emulation and Simulation

Whereas Layers 1 to 5 provide, in a sense, the infrastructure required, the intelligence of a digital twin is added in Layer 6 (**Fig. 3**). Since this layer is highly dependent on the actual application, little can be specified in a general architecture. This layer could implement any of the roles of a digital twin that are listed at the end of Section 2. These roles would, in general, rely on having access to emulations (that model current behavior) and simulations (that model future or potential behavior) of the physical twin. Some of the roles will require the development of custom software, but some can be accomplished using commercially available plant simulation software, such as Siemens Tecnomatix Plant Simulation. The software itself may be cloud-based or may operate from a conventional computer and access the database in the cloud.

To realize the diverse potentials of digital twins through connectedness in cyberspace, Layer 6 should exchange information with the physical twin via the cloud-based data repositories. Some simulation applications, such as Tecnomatix Plant Simulation, include the ability to interface with databases using protocols such as MySQL.

However, in simple cases, Layer 6 could even exchange information with the OPC UA layer without requiring the intermediate layers of the architecture. Some simulation software provided by major automation vendors, such as Tecnomatix Plant Simulation, have provision for interfacing with OPC UA servers. This approach would be appropriate where the plant simulation is closely tied to the details of the physical twin's implementation and architecture.

5 Evaluation Through Case Study

To evaluate the effectiveness of the six-layer architecture illustrated in **Fig. 3**, an implementation of the architecture was created as a case study. The case study focused on confirming that the infrastructure provided by the architecture is functional and therefor considered the movement of data between the different layers. The case study also presents a set of tools and platforms that can be used to implement the six-layer architecture.

5.1 Local Data Repositories

As shown in **Fig. 3**, Layer 3 must be able to communicate with local automation controllers (Layer 2), cloud-based databases (Layer 5), the IoT Gateway (Layer 4) and, in some cases, with the plant simulation (Layer 6). Various OPC servers available from reputable vendors have the potential to be used in Layer 3. For the case study, KEPServerEX from Kepware Technologies was selected, with access to more than 150 data source drivers. The server was configured on a PC and connected to a Siemens SIMATIC S7-1200 PLC controller (Layer 2) using Siemens TCP/IP driver communication.

KEPServerEX is also easy to interface directly with Layer 5, through its Datalogger advanced plug-in. The Datalogger supports any ODBC-compliant database management system. The Datalogger detects any change in value within a user-defined "log group" on the OPC UA server and sends the new data value, a timestamp and a quality measure [20] to the database. Data can also be transmitted from Layer 5 to the OPC UA server (Layer 3), triggered by a data change in Layer 5. The connection is made possible on the OPC UA server with a Kepware ODBC client driver and the "advanced plug-in" in KEPServerEX.

When setting up the driver on the OPC UA server, using the advanced plug-in, user-selected database entries are linked to tag names on the OPC UA server. The ODBC driver monitors the database for any changes to the selected database entries, accesses the data from the database using the MySQL protocol and registers the new values in the OPC UA server. OPC UA then autonomously updates the corresponding registers in the controller in Layer 2, thereby completing the communication of data changes from the database in the cloud to the physical twin.

The interface between Layer 6 and Layer 3 is described in Section 5.4

5.2 IoT Gateway

The IoT Gateway in Layer 4 (**Fig. 3**) must interface with the local data sources on Layer 3 and with the databases on Layer 5. It also provides a convenient location of a GUI to manage the digital twin. For the case study, a custom C# program was developed as the IoT Gateway. C# offers a number of relevant features, as illustrated in the discussion below. Other programming languages can also be considered, but particularly the language's compatibility with OPC drivers and database interfaces should be considered.

The IoT Gateway acts as an OPC UA client to exchange data with Layer 3. In the case study, this was accomplished through the ClientAce OPC Client Toolkit. The client drivers provide convenient access to OPC UA and other OPC server applications. The ClientAce toolkit is available for .NET applications, which is inherently suited to C#. The ClientAce driver continuously monitors the OPC UA server for changes to the values associated with a user-selected set of tags. If a change is detected, the driver activates a call-back function which allows the IoT Gateway to interpret and process the changes.

In the case study, the IoT Gateway connects to a SQL database on Layer 5 using MySQL communication protocol. C#, through the .NET library, provides various components that simplify the interfacing with the database. The IoT Gateway periodically polls the database to detect any changes in the database initiated by Layer 6, i.e. by the plant simulation or other applications interacting with the database. The interval between consecutive polls can be set through the GUI.

An aspect that was not initially considered arose during the testing: the date and time of the various layers need to be synchronized or, at least, the IoT Gateway should be aware of that the hosts of the different layers may be in different time zones. The default time they use could be their local time or Coordinated Universal Time (UTC).

An existing cryptography, PBKDF2, using SHA1 (Secure Hash Algorithm) as underlying hash function, was implemented for secure user login and authentication. A "salt" is generated using a Cryptographically Secure Pseudo-Random Number Generator (CSPRNG) and hashed with the password using the PBKDF2 algorithm [21].

5.3 Cloud-based Information Repository

The information repository in cyberspace is shown as Layer 5 in **Fig. 3**. Cloud storage and Open Database Connectivity (ODBC) platforms were not extensively evaluated for the case study, since the choice of platform will be highly dependent on the context. The architecture presented here assumes that the developers of a digital twin, being closely associated with the developers of the physical twin, will not have the interest in or expertise for developing its own cloud platform and will buy this service from one of the many available providers.

For the case study, as a matter of convenience, Google Cloud Platform was chosen as the information repository. In practice, security and reliability considerations will probably lead to the use of a platform that is paid for.

5.4 Emulation and Simulation

Siemens Tecnomatix Plant Simulation (PS) was selected as simulation program for the case study. It is suitable for visualizing the physical production system or physical twin in soft real-time and allows the integration of a physical system with the virtual environment. Tecnomatix PS enables the simulation, visualization, analysis and optimization of production systems and logistics processes [22].

As illustrated in **Fig. 3**, Tecnomatix PS is equipped with an ODBC interface that is able to retrieve data based upon real events from the physical twin via the cloud-based database. Tecnomatix PS is also able to obtain real-time data directly from the OPC UA server. Data can therefore be transferred from Layer 2 to Layer 6 without the need to know each other’s native protocol.

5.5 Testing

Testing showed that the case study configuration described above was capable of communicating a change in the state of the physical equipment (e.g. triggering a switch) through the layers, up to the Tecnomatix PS in Layer 6. Also, a data change commanded from Layer 6 was communicated to an actuator in the physical equipment. The bidirectional communication was demonstrated via Layer 5, with and without the use of Layer 4, as well as directly between Layer 3 and Layer 6.

6 Conclusion

The paper presents a multi-layer architecture that provides the infrastructure required for a digital twin within the CPPS paradigm. The architecture is independent of the application-specific details and aimed here specifically at manufacturing cells, but may have wider application. The architecture provides for a local data layer (e.g. OPC UA or databases local to the plant), an IoT Gateway layer that relays information between the physical world and cyberspace, a layer with cloud-based data repositories and, finally, a layer with emulation and simulation software.

The architecture clarifies the different roles required to pass the data and information between the physical twin and the part of the digital twin that hosts its intelligence. Using readily available technologies and services, such as OPC UA servers and cloud-based database services, provides reliability, security and reduces the digital twin developers' expertise requirements and development risks. The custom development work is mostly focussed on one layer, i.e. in the IoT Gateway. The IoT Gateway also provides for conflict resolution, safety functions and a GUI.

Some limiting factors revealed during a case study evaluation include the effect of latency and slow connection to the online cloud server, as well as the complex installation of some OPC UA drivers required for the development of the IoT Gateway. The drivers are susceptible incompatible versions of the drivers and the development environment.

References

1. Kagermann, H., Wahlster, W., Helbig, J.: Securing the future of German manufacturing industry: Recommendations for implementing the strategic initiative INDUSTRIE 4.0. acatech, Final Rep. Ind. 4.0 Work. Gr. (2013).
2. Monostori, L.: Cyber-physical production systems: Roots, expectations and R&D challenges. Procedia CIRP. 17, 9–13 (2014).
3. VDI/VDE: Cyber-Physical Systems: Chancen und Nutzen aus Sicht der Automation. Gesellschaft Mess und Autom. (GMA), Thesen und Handlungsfelder. (2013).
4. Monostori, L., Kádár, B., Bauernhansl, T., Kondoh, S., Kumara, S., Reinhart, G., Sauer, O., Schuh, G., Sihn, W., Ueda, K.: Cyber-physical systems in manufacturing. CIRP Ann. - Manuf. Technol. 65, 621–641 (2016).
5. Shafto, M., Conroy, M., Doyle, R., Glaessgen, E.: DRAFT Modeling, Simulation, information Technology & Processing Roadmap. Technol. Area. (2010).
6. Cearley, D.: Gartner's Top 10 Strategic Technology Trends For 2017, https://www.forbes.com/sites/gartnergroup/2016/10/26/gartners-top-10-strategic-technology-trends-for-2017/#629bc186b336.
7. Oracle: Digital Twins for IoT Applications: A Comprehensive Approach to Implementing IoT Digital Twins. , Redwood Shores (2017).

8. Feuer, Z., Weissman, Z.: The value of the digital twin, https://community.plm.automation.siemens.com/t5/Digital-Transformations/The-value-of-the-digital-twin/ba-p/385812.
9. Waterman, P.J.: Manufacturing in the World of Industrie 4.0, http://www.digitaleng.news/de/manufacturing-in-the-world-of-industrie-4-0/.
10. Grieves, M.: How A “Digital Twin” Can Warrant Products Are Built As Designed, https://www.mbtmag.com/article/2015/01/how-%E2%80%98digital-twin%E2%80%99-can-warrant-products-are-built-designed.
11. Bagheri, B., Lee, J.: Big future for cyber-physical manufacturing systems, http://www.designworldonline.com/big-future-for-cyber-physical-manufacturing-systems/.
12. Marr, B.: What Is Digital Twin Technology - And Why Is It So Important?, https://www.forbes.com/sites/bernardmarr/2017/03/06/what-is-digital-twin-technology-and-why-is-it-so-important/#26203f1c2e2a.
13. Martin, J.: The Value of Automation and Power of the Digital Twin, https://newsignature.com/articles/value-automation-power-digital-twin/.
14. M.A.C. Solutions: KEPServerEX V6 OPC Server, https://www.mac-solutions.net/en/products/industrial-data-comms/opc-communications-suite/item/157-kepserverex-v6-opc-server.
15. OPC Foundation: Update for IEC 62541 (OPC UA) Published, https://opcfoundation.org/news/opc-foundation-news/update-iec-62541-opc-ua-published/.
16. OPC Foundation: OPC Unified Architecture Secure communication with IEC 62541 OPC UA, https://opcfoundation.org/wp-content/uploads/2014/05/OPC-UA_Security_EN.pdf.
17. Hoppe, S.: There is no Industrie 4.0 without OPC UA. OPC Found. (2017).
18. Lee, J., Bagheri, B., Kao, H.-A.: A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems. Soc. Manuf. Eng. 3, 18–23 (2014).
19. Technopedia: What is Data Intelligence?, https://www.techopedia.com/definition/28799/data-intelligence.
20. PTC Inc: ClientAce User Manual, https://www.kepware.com/en-us/products/clientace/documents/clientace-manual.pdf.
21. Defuse Security: Salted Password Hashing - Doing it Right, https://crackstation.net/hashing-security.htm.
22. Siemens: Plant Simulation, https://www.plm.automation.siemens.com/en/products/tecnomatix/manufacturing-simulation/material-flow/plant-simulation.shtml#lightview%26url=/en_us/Images/7541_tcm1023-4957.pdf%26title=Tecnomatix Plant Simulation%26description=Simulate, visualize, analyze.