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Procedia Computer Science 217 (2023) 640–649

Procedia Computer Science

www.elsevier.com/locate/procedia

4th International Conference on Industry 4.0 and Smart Manufacturing

On the development of the Digital Shadow of the Fischertechnik Training Factory Industry 4.0: an educational perspective

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Abstract

The fourth industrial revolution is characterized by the increasing availability of data, which can be collected from machines to create digital counterparts of them (e.g., Digital Shadow, Digital Twin), understand their status, and drive strategic and operational decisions. To effectively create and use such digital counterparts, it is necessary to hire skilled people or train them to achieve the necessary competencies, for instance using learning factories, which are nowadays becoming more and more common. From an educational standpoint, it is interesting to observe how such competencies could be developed starting from a personal background. The paper describes the development process of the Digital Shadow of the Fischertechnik Training Factory Industry 4.0 in the context of a university course. The aim was to understand if the competencies acquired during the Computer Science bachelor's degree were enough to allow for the development of a functioning Digital Shadow of the learning factory.

Keywords: Digital Twin; Digital Shadow; Learning Factory; Industry 4.0; Bloom's Taxonomy;

1. Introduction

The manufacturing world is witnessing a revolution that is changing the way stakeholders approach production processes and business relations. Since the beginning of the fourth industrial revolution, value generation from data has been one of the most studied fields for researchers and practitioners [1]. While unprecedented data generation has been among the most important acknowledged effects of the digitalization of manufacturing processes, it has required questioning how to make use of such data to exploit their availability [2], avoiding falling into the paradox of collecting data just because it is possible to do so, having to suffer storage cost but not generating value from data.

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10.1016/j.procs.2022.12.260

The digitalization of production processes has been more and more commonly associated with the concept of Digital Twin (DT), defined (in a simplified way) as a digital counterpart of a physical object by [3]. In their paper, the authors of [3] clarify that it is necessary to distinguish between the possibilities of the twinning act, depending on the kind of data exchange existing between the physical and digital counterparts.

Depending on the typology of data exchange between the physical and digital components, [4] defines the Digital Model (i.e., manual data exchange between physical and digital and vice versa), Digital Shadow (i.e., automatic data exchange from physical to digital, manual from digital to physical), or Digital Twin (i.e., automatic data exchange from physical to digital and vice versa).

The possibilities provided by DTs (at every level of development) fall into the category of augmented decision-making support, allowing to perform complex scenario analysis to evaluate alternatives and make informed decisions [5]. To do so, and be able to exploit DTs and scenario analysis at best, decision-makers and employees need to understand their functioning and cope with the data used [6].

The concept of a "learning factory" started spreading following the creation of controlled places where employees and/or students can learn the functioning of a production process in a controlled environment, study the various behaviour that the system may assume, and learn how to respond to such behaviours [7]. Depending on the role covered, students need to understand how to exploit the DTs possibilities and/or understand how they are created and work.

The aim of the paper is twofold. On the one hand, the aim is to describe the process of creation of the Digital Shadow of the Fischertechnik Training Factory Industry 4.0. On the other, the aim is to pay attention to the educational setting used for the process, where bachelor students were required to develop the Digital Shadow in a more or less autonomous way. Other papers discussed the possibility to use the Fischertechnik Training Factory Industry 4.0 to explain the Digital Twin concept in an educational environment [8], but none, to the best of the authors' knowledge, discussed an application case where students were required to develop a digital counterpart of the Factory and connecting this process to the Bloom's taxonomy of learning – i.e., a framework classifying the expected learning outcome as a result of an instruction process [9].

The paper is structured as follows: section 2 provides a short theoretical background for the paper. Section 3 describes the Fischertechnik Training Factory Industry 4.0, while Section 4 the work methodology used by the students to develop the Digital Shadow. Section 5 describes the Digital Shadow and its main components. Section 6 provides an overview of the lesson learned in the process, while Section 7 concludes the paper, also providing future directions for the research on the educational approach and the development of the Digital Shadow.

2. Theoretical Background

Industry 4.0 indicates a technological revolution driven by the digitalisation of physical production and business processes in manufacturing companies in the scope of enhancing their management and increasing their effectiveness and productivity [10]. Despite the possibilities offered by such an enhancement, companies are facing many challenges in their transition, going from the technological and infrastructural requirements required to run state-of-the-art-like processes to the necessity to find human resources able to deal with such transition [11, 12]. Specifically, companies are requiring specific skill sets for employees able to deal with digital processes characterized by intense data generation and collection that has to lead to valuable data use during the decision-making phase to generate added value for the stakeholders [13].

The training of employees may require time-consuming and costly sessions, which may put at risk the employees' safety and infrastructure health. For this reason, learning factories started spreading over the years, since they guarantee the possibility to recreate various working conditions in a realistic environment at a cheaper cost. In particular, training factories aim to allow employees to learn how to behave in various situations and speed up their decision-making skills to reduce losses in the real environment [14].

Specifically, one of the most discussed possibilities brought to the industry by the unprecedented data availability is the creation of realistic digital counterparts of physical objects, frequently referred to as Digital Twins [4].

Several papers discuss applications of Digital Twins, or related concepts, in manufacturing companies [15–18]. Thus, having, at least, a basic understanding of its functioning is a competence that employees are required to have. In addition, employees must be able to handle complex situations not covered during the training in the learning factories. To do so, they must be able to understand the meaning of the information coming from the field and find solutions able to cope with or solve the problem.

From a pedagogical perspective, it is necessary to understand what kind of skills should be owned by actors and how to teach these skills, so that the actors would be able to manage unexpected situations and overcome problems having the required technical, methodological, social, and personal competencies [19]. Despite not being developed specifically for Industry 4.0 problems, Bloom's taxonomy can be used to guide the definition of the learning goals for the actors [9].

Bloom's taxonomy intends to serve various goals like a) defining a common language for communication of learning goals, b) creating the bases or the definition of a course or curriculum and, c) determining the congruence of educational objectives, activities, and assessment units. The levels of the taxonomy proposed by [9] are detailed in Table 1.

Table 1. Revised Bloom's taxonomy [9]

Verb	Description
Remember	Retrieving relevant knowledge from long-term memory
Understand	Determining the meaning of instructional messages, including oral, written, and graphic communication
Apply	Carrying out or using a procedure in a given situation
Analyse	Breaking material into its constituent parts and detecting how the parts relate to one another and t an overall structure or purpose
Evaluate	Making judgments based on criteria and standards
Create	Putting elements together from a novel, coherent whole or making an original product

Thus, educators could use Bloom's taxonomy as a reference to define learning goals for students, being them in the university or industrial context. Such taxonomy could be used to define prerequisites to be owned by the students and then define learning activities based on the required outcome. In the remaining of the paper, it will be explained how the researchers tested the learning level of a group of Computer Science bachelor's students to evaluate their capability of developing a Digital Shadow of the Fischertechnik Training Factory Industry 4.0. The test was used to verify that, based on their educational background, they could construct a Digital Shadow of the Factory putting together their previous knowledge to create something new, positioning them on the "create" level of Bloom's taxonomy.

3. The Fischertechnik Training Factory Industry 4.0

The Fischertechnik Training Factory Industry 4.0 (FTF4.0), depicted in Fig. 1, is a learning factory developed to learn how digitalisation could affect production processes, allowing users to understand the meaning of real-time monitoring and visualization of production data on dashboards.

The factory is composed of five modules:

- High-Bay Warehouse (HBW)
- Vacuum Gripper Robot (VGR)
- Delivery and Pickup Station (DPS)
- Multi-Processing Station with Oven (MPO)
- Sorting Line with Color Detection (SLD)

Each one of these modules has a controller able to communicate with the main one, which manages the data flow from the physical FTF4.0 to the online dashboard through an MQTT protocol. Each section of the FTF4.0 has a deposit area where the piece worked is delivered before and after the processing.

Each module of the FTF4.0 has a storage area where the piece is delivered before and after the processing before being moved to the next stage. The delivery of a piece in the storage area determines the beginning of the activity of that module, while the collection of the piece to be moved to the following module sets the end of the module activity. The transfer of the worked piece from one module to the following one is performed by the VGR that, using a vacuum suction cup, hooks the piece and moves it to its destination. In the factory, three kinds of pieces only differing in their colour (i.e., blue, white, or red) are available. Every piece has an NFC tag inside that is read every time a new piece is introduced in the cycle. In this way, the system always knows how many and what kind of pieces are in the system.

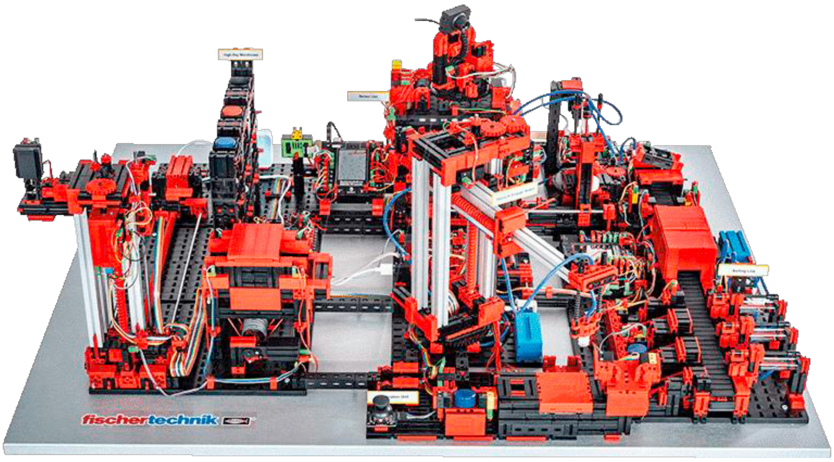

Fig. 1. Fischertechnik Training Factory Industry 4.0

The factory has a standard cycle that follows this sequence:

1. A piece is placed in the entrance area. The sensor read the presence of the piece and requests the VGR to move to hook it.
2. The piece is moved to the NFC reader area, where the ID code of the piece is read and sent to the cloud.
3. The VGR moves the piece to the HBW area, where the piece is stored.
4. Using the online dashboard, the users place an order selecting the colour of the piece they are interested in.
5. The HBW withdraw the piece of the selected colour.
6. The VGR moves the piece to the MPO and places it in the storage area.
7. The piece is worked in the MPO.
8. The piece is moved to the SLD.
9. The piece is sorted based on the colour and then placed in the exit area using the VGR.

While the users can oversee the whole process by looking at the physical factory, they are also required to interact with an online dashboard (Fig. 2) to place orders and get information on the process status.

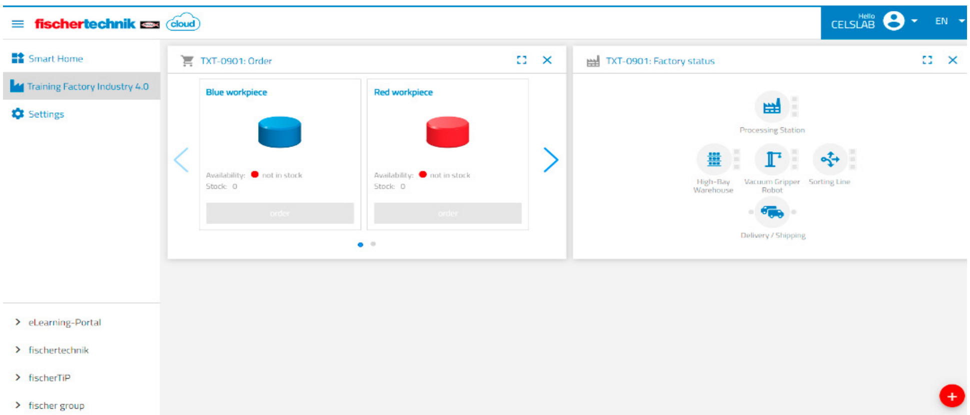

Fig. 2. Fischertechnik dashboard

While the FTF4.0 might be useful to allow students to comprehend the functioning of production processes in an Industry 4.0 setting, in its delivery status it does not provide much flexibility to the users in terms of processing times and simulation possibilities.

For these reasons and given the limits of the hardware available on the FTF4.0 in terms of receiving external inputs, the authors decided to use it as a test bench to allow students to learn how to create a Digital Shadow of a production process following the learning levels and approaches proposed by the Bloom's taxonomy.

4. Work methodology

Five students, working as a group, were selected to run the test in the context of a university course and were given the goal of developing the Digital Shadow of the FTF4.0. The students, enrolled in the Computer Science bachelor program, had a basic knowledge of communication protocols as well as python programming language.

The students had no previous experience or training in the use of the AnyLogic software, which was the software selected by the authors to simulate the production process, or Node-Red, the software used to create the custom dashboard. The students had to learn how to use AnyLogic and the basics of hybrid simulation to complete the task, as well as understand how to use the knowledge acquired during their educational path to creating a connection between the physical factory and the digital model, creating thus the Digital Shadow of the FTF4.0.

Methodologically, the students did:

- Analyse the Fischertechnik FTF4.0 documentation.
- Identify the components of the FTF4.0.
- Test the FTF4.0 functionalities to understand the process and the data communicated by the FTF4.0.
- Analyse the Node-Red documentation.
- Create the custom dashboard with Node-Red.
- Wrote the python code to scrape data from the custom dashboard.
- Create the 3D simulation model in AnyLogic and synchronize it with the physical FTF4.0.
- Create a connection between the custom dashboard and the AnyLogic model using the python code and the pipeline library [20], which is a library used by AnyLogic to read and run python code.
- Test the Digital Shadow of the FTF4.0.

5. The development of the Digital Shadow

As mentioned in the previous section, students were provided with general indications to develop the FTF4.0 Digital Shadow. This section aims at discussing how the students achieved each intermediate milestone and the final result.

5.1. Development of a custom dashboard using Node-Red

Node-Red is a development tool that allows, using a graphical representation, to develop a connection between hardware and software (Fig. 3). In this case, Node-Red was used to read and process the data collected from the FTF4.0 main controller. By using JSON data format, Node-Red allows for easy data exchange in terms of reading and writing tasks.

Using Node-red and the MQTT protocol, it has been possible to define a custom dashboard. Specifically, once understood the functioning of the Node-Red tool, the students referred to the Fischertechnik documentation to understand the data communicated by the controllers. By doing so, it has been possible to associate each module with the data communicated, cluster them and, eventually, visualize them in a custom dashboard (Fig. 4). Specifically, by exploiting the data communicated through the MQTT protocol, the custom dashboard can show, in each moment, the status of the components.

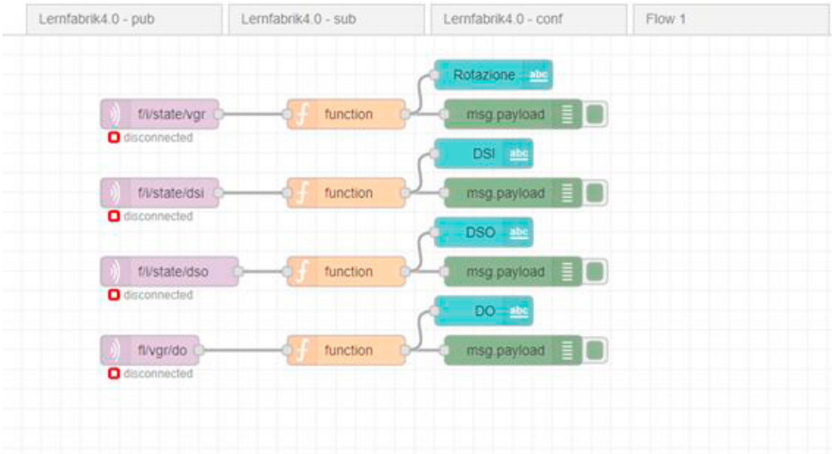

Fig. 3. Node-Red

Fig. 4. Custom dashboard

5.2. Development of a python code to scrape data from the custom dashboard

Once created the dashboard, the students were required to develop a method to automatically extract data from it in the scope of allowing the simulation model (i.e., the Digital Shadow of the FTF4.0) to update in real-time the simulation. To do so, the students chose to code a python script able to scrape data from the custom dashboard. To code the script, it was first necessary to clarify the values that each variable in the code may assume, as shown in Table 2.

Following the identification and classification of the values assumable by the variables, the python code was written exploiting libraries such as BeautifulSoup [21] and Selenium [22] in support of the web scraping task. To execute the scraping, it has been necessary to analyze the content of the web page displaying the dashboard and match the variables in the table and on the website with the ones belonging to the python code. To avoid compatibility problems and errors preventing the scraping task, a web driver developed for Microsoft Edge (the browser used to open the dashboard and execute the scraping) was adopted.

Table 2. Variables and possible values

Variable	Description	Possible values
Rotazione	State of the VGR	• Stopped • Moving
DSI	Sensor for incoming pieces	• Piece absent • Piece present
DSO	Sensor for outcoming pieces	• Piece absent • Piece present
DO	Status of the process	• Exit • Take box • Piece entered • Hold piece for processing • Empty box • Reset • Calibration • MPO working
Intervallo	Time for activity execution	• Time (s)
Movimentazione Magazzino	Status of the HBW	• Stop • Moving
ACK	Processing station is working or stopped correctly	• 1 • Fine
Tempo	Timestamp when the piece enters or exits one station	• gg/mm/yyyy, hh:mm:ss
Lavorazione	Status of the MPO	• Stop • Executing
Divisione	Sorting process stopped or executing	• Stop • Executing

5.3. Development of the Digital Shadow of the FTF4.0

A reproduction of the FTF4.0 production process was created using the Process Modelling, Material Handling, and Agent libraries of AnyLogic. To recreate the process, the hybrid simulation paradigm was chosen. This choice was due to the necessity to mix the Discrete-Event Simulation (DES) paradigm – useful to create the process flowchart – and the Agent-Based Simulation (ABS) paradigm – useful to model the behaviour of the modules composing the process (e.g., moving, stop) and the pieces worked.

A flowchart of the process (Fig. 5) was created to use it as a guide for the real-time 3D representation (Fig. 6). The connection between the custom dashboard and the simulation model in AnyLogic was provided through the python script and the Pypeline [20] library. Given the process and the movement timing of the FTF4.0, it was decided to schedule an automatic update of the data collected by the simulation model every 2 seconds, this means that every 2 seconds the python script scrapes the data from the custom dashboard, read the status of the process, and uses it to update the simulation model in AnyLogic.

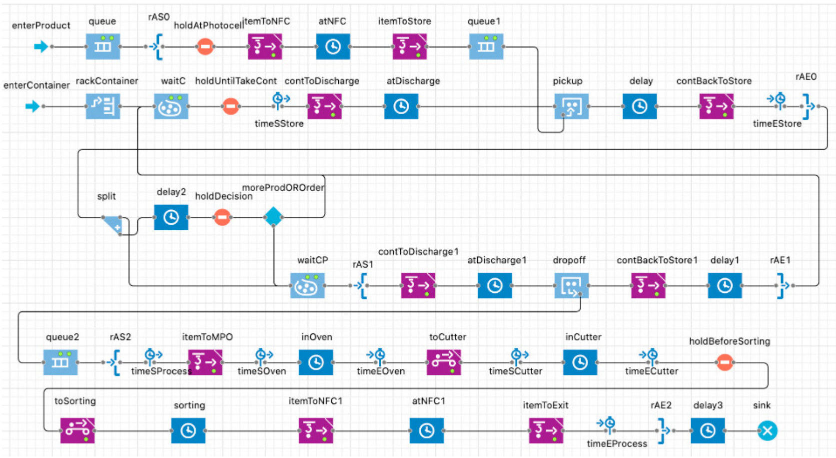

Fig. 5. Flowchart

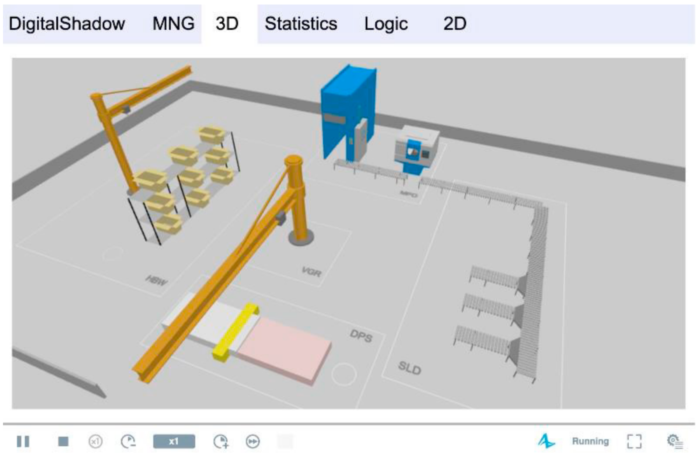

Fig. 6. 3D model

6. Discussion

At the end of the course, the students were able to develop and run the Digital Shadow of the FTF4.0. During the process, students learned how to manage and solve communication issues between the physical FTF4.0 and digital counterpart represented in AnyLogic as well as the logic underneath the development of a Digital Shadow.

Overall, the task required the students 5 months of work to be completed. The time frame was aligned with the expectations of the authors since students were required to study the FTF4.0 functioning and, in some cases, acquire new skills and competencies. Students were qualitatively evaluated based on their capacity to find solutions to unexpected problems both relying on competencies acquired in the past, new ones and/or a mix of them. Based on the outcome, a positive evaluation was given to the students. Both physical and software problems emerged, and the students were able to solve them by exploiting all the instruments available (e.g., software documentation, course material, brainstorming and critical thinking).

The development of the Digital Shadow required understanding the complexity generated by the creation of a digital replica of a physical object. Troubleshooting sessions dedicated to the messages and errors generated by the FTF4.0 took time to be analysed and coped with. The students acquired new skills in terms of process modelling, learning the Discrete Event Simulation paradigms as well as understanding how to model the behaviour of the modules composing the process in the Agent-Based part of the Digital Shadow. In addition, they were able to adapt the coding skills acquired in other university courses for the task they were assigned.

During the development of the Digital Shadow, only a minimum of help was provided to them, only related to generic suggestions related to the methodological approach or parts of code with some initial problem.

According to the descriptions of Bloom's Taxonomy level reported in Table 1, students positioned themselves at the "Create" level, being able to reinterpret the knowledge acquired over the years and use it to create the Digital Shadow of the FTF4.0. In particular, the students were positioned at the "Create" level due to the way the problem was set – developing the Digital Shadow with only general indications provided in support – and how they carried it out. Being so autonomous, they demonstrated to be sufficiently skilled to evaluate problems and make decisions able to overcome them to achieve their objective. The Bloom's Taxonomy contains also the "Apply" level, in which students follow a detailed, given, approach to solve a problem. In the authors' opinion, the students could not be positioned at this level because of the way they approached the problem and because no structured or pre-defined work methodology was given to them. They have been required to think about each step and choose the best method/approach leading to the following one, solving one problem at a time a building the final result on the outcome of the steps they faced in the development. The "Analyse" and "Evaluate" levels were partially touched during the development process, since the students were required to decompose the problem into elementary parts ("Analyse") and select the right solution ("Evaluate") to move to the following step in the development process. The "Remember" and "Understand" levels were considered as acquired since the beginning of the process.

7. Conclusions

The digitalization of business and production processes is becoming more and more common among manufacturing companies, which can leverage it to make more informed decisions related to production schedules or activities in support of it. To do so, companies need personnel able to create digital counterparts reliably.

The paper discussed the process of creation of a Digital Shadow of the FTF4.0 made by students during a university course. Students were given the goal of creating a DS with only the indication of the tool to use for the simulation part (AnyLogic) and some intermediate milestones to achieve (e.g., creation of the dashboard, verify the communication between the dashboard and the model). The aim was to test how the students would position according to Bloom's Taxonomy and check whether and how they would be able to use the knowledge acquired in their educational path to creating something new answering a specific industry-related problem in a controlled scenario. By using tools such as Node-Red, python, and AnyLogic, the students were able to extract data from the physical asset, send the data to the custom dashboards, scrape the data and, following, continuously update the simulation model, creating the Digital Shadow.

Considering the minimum help required to carry out the task, it was possible to position them on the "Create Level" of Bloom's Taxonomy, since they were able to manage autonomously all the tasks.

At this stage of development, the model is only able to replicate the behaviour of the FTF4.0, without providing scenario analysis capabilities. In the next future, the aim will be to implement such a possibility to extend the usage of the DS. Possibly, with the acquisition of new sensors and instrumentation, and a higher level of personalization, it would be possible to increase the capabilities of the FTF4.0 allowing for the transformation of the Digital Shadow into a Digital Twin.

Acknowledgements

This work was co-funded by the European Commission through the BLISS Project, GA 2021-1-SE01-KA220-HED-000023166, under the Erasmus+ Programme.

References

[1] Khan, Maqbool, Xiaotong Wu, Xiaolong Xu, and Wanchun Dou. (2017) 'Big data challenges and opportunities in the hype of Industry 4.0'. in *IEEE International Conference on Communications* Institute of Electrical and Electronics Engineers Inc.;
[2] Belhadi, Amine, Karim Zkik, Anass Cherrafi, Sha'ri M. Yusof, and Said El fezazi. (2019) 'Understanding Big Data Analytics for

Manufacturing Processes: Insights from Literature Review and Multiple Case Studies'. *Computers & Industrial Engineering* **137** : 106099.

[3] Errandonea, Itxaro, Sergio Beltrán, and Saioa Arrizabalaga. (2020) 'Digital Twin for maintenance: A literature review'. *Computers in Industry* **123** : 103316.

[4] Kritzinger, Werner, Matthias Karner, Georg Traar, Jan Henjes, and Wilfried Sihn. (2018) 'Digital Twin in manufacturing: A categorical literature review and classification'. *IFAC-PapersOnLine* **51** (**11**): 1016–22.

[5] Cortés, Daniel, José Ramírez, Luis Villagómez, Rafael Batres, Virgilio Vasquez-Lopez, and Arturo Molina. (2020) 'Digital Pyramid: an approach to relate industrial automation and digital twin concepts'. in *2020 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)* IEEE; p. 1–7.

[6] Rosin, F., P. Forget, S. Lamouri, and R. Pellerin. (2021) 'Impact of Industry 4.0 on decision-making in an operational context'. *Advances in Production Engineering & Management* **16** (**4**): 500–14.

[7] Sudhoff, Martin, Christopher Prinz, and Bernd Kuhlenkötter. (2020) 'A Systematic Analysis of Learning Factories in Germany - Concepts, Production Processes, Didactics'. *Procedia Manufacturing* **45** : 114–20.

[8] Heschl, Lukas, Thomas Dilger, Reinhard Bernsteiner, and Christian Ploder. 'Digital Twin: decreasing the cognitive load by using Industry 4.0 simulation'.

[9] Krathwohl, David R. (2002) 'A revision of Bloom's taxonomy: An overview'. *Theory into practice* **41** (**4**): 212–8.

[10] Hercko, Jozef, Jozef Her, Eva Slamková, and Jozef Hnát. (2015) 'Industry 4.0 as a factor of productivity increase'. in *Proceedings of TRANSCOM PROCEEDINGS 2015-11th European Conference of young researchers and scientists* p. 188–122.

[11] Jaskó, Szilárd, Adrienn Skrop, Tibor Holczinger, Tibor Chován, and János Abonyi. (2020) 'Development of manufacturing execution systems in accordance with Industry 4.0 requirements: A review of standard- and ontology-based methodologies and tools'. *Computers in Industry* **123** : 103300.

[12] Sahal, Radhya, John G. Breslin, and Muhammad Intizar Ali. (2020) 'Big data and stream processing platforms for Industry 4.0 requirements mapping for a predictive maintenance use case'. *Journal of Manufacturing Systems* **54** : 138–51.

[13] Pereira, A.C., and F. Romero. (2017) 'A review of the meanings and the implications of the Industry 4.0 concept'. *Procedia Manufacturing* **13** : 1206–14.

[14] Sima, Violeta, Ileana Georgiana Gheorghe, Jonel Subić, and Dumitru Nancu. (2020) 'Influences of the Industry 4.0 Revolution on the Human Capital Development and Consumer Behavior: A Systematic Review'. *Sustainability* **12** (**10**): 4035.

[15] Ladj, Asma, Zhiqiang Wang, Oussama Meski, Farouk Belkadi, Mathieu Ritou, and Catherine Da Cunha. (2021) 'A knowledge-based Digital Shadow for machining industry in a Digital Twin perspective'. *Journal of Manufacturing Systems* **58** : 168–79.

[16] Bergs, Thomas, Sascha Gierlings, Thomas Auerbach, Andreas Klink, Daniel Schraknepper, and Thorsten Augspurger. (2021) 'The Concept of Digital Twin and Digital Shadow in Manufacturing'. *Procedia CIRP* **101** : 81–4.

[17] Franzen, Julian, Jannis Stecken, Raphael Pfaff, and Bernd Kuhlenkötter. (2019) 'Using the Digital Shadow for a Prescriptive Optimization of Maintenance and Operation'. in Uwe Clausen Sven Langkau and Felix Kreuz (eds.) *Advances in Production, Logistics and Traffic* Cham: Springer International Publishing; p. 265–76. (Lecture Notes in Logistics).

[18] Lu, Yuqian, Chao Liu, Kevin I.-Kai Wang, Huiyue Huang, and Xun Xu. (2020) 'Digital Twin-driven smart manufacturing: Connotation, reference model, applications and research issues'. *Robotics and Computer-Integrated Manufacturing* **61** : 101837.

[19] Hernandez-de-Menendez, Marcela, Ruben Morales-Menendez, Carlos A. Escobar, and Megan McGovern. (2020) 'Competencies for Industry 4.0'. *International Journal on Interactive Design and Manufacturing (IJIDeM)* **14** (**4**): 1511–24.

[20] Tyler-Wolfe, Adam. 'Pypeline'.GitHub.

[21] Richardson, L. (2007) 'Beautiful soup documentation.'

[22] Bowen, Dillon. (2020) 'Selenium-Tools'.