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Applying Digital Twin Technology in Higher Education: An Automation Line Case Study

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Abstract. Production systems are being expanded to include Digital Twins (DTs) as part of increased industrial digitalization. DTs can bring benefits e.g., increase visibility, safety, and accessibility of the system. Further, digital experimentation can reduce time and cost. Though, application of DT technologies involves challenges i.e., model accuracy or errors in transferring data or codes between the DT and the physical twin. Many studies on DTs focus on industrial applications. However, DT technology has potential for implementation of digital labs in education. This aspect of DTs is of rising importance as distance education has increased over the last decade and access to physical laboratories can be restricted due to factors such as the Covid-19 pandemic. Thus, there is a need to study the use of DT technology in higher education. To address this, we investigate possibilities and challenges of applying DT technology in education to conduct industrial-like labs virtually. A case of an automation line, with full scale industrial equipment, based at a research center, is focused. Results emphasize that the application of DT technologies require multi-domain expertise to understand the consequences of every single decision in the design process on every piece of equipment involved, making the modelling process complex and time consuming. Thus, when applied in education, test procedures need to be designed to focus on students' motivation, improved learning and understanding of production systems. DTs are considered enabling technologies supporting the concept of Industry 5.0, thus stressing the human-centric aspects of advancing Industry 4.0. The predicted application of DTs emphasizes the need for educational curricula that include laboratory applications and theoretic understanding of DT technologies. This study focusses the application of DT technologies in higher education curricula, but the result of the study can contribute to other areas such as automation and virtual commissioning towards smarter manufacturing.

Keywords. digital twin, cyber-physical, seamless transfer, virtual labs, virtual commissioning

1. Introduction

Society is moving through a transition of increased digitalization, in the era of Industry 4.0 (I4.0) involving emerging advances in for example, artificial intelligence, Internet of Things, cyber-physical systems, and big data analysis [1]. This has led to the recognition of the importance of human interaction and critical thinking leading I4.0 into Industry

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5.0 (I5.0) [2] i.e., towards sustainability, human-centricity, and resilience [3]. Among specifically identified enabling advances for I5.0 are digital twins (DTs) and simulation i.e., production optimizing, and testing of operational safety [4]. DTs are digital replicas that use 3D modeling and sensors to create digital representations [5]. One of the emerging enabling factors for DT technology are the internet of things (IoT) and the possibility to collect data in real time [5]. Production systems are being expanded to include DTs as a step towards increased industrial digitalization [6]. DTs can bring benefits e.g., increase visibility, safety, and experimentation can be conducted virtually, thus reducing time and cost [7]. However, successful model building of DTs involve challenges such as model accuracy, connection to uncalibrated entities, errors in transferring data or codes between the DT and the real system. Other issues are data acquisition and validation, data fusion accuracy, the computational process, and time to analyze data and send responses to the physical twin [7].

In addition to manufacturing or other fields, DTs can be used for conducting virtual labs on real equipment for educational purposes. It is recognized that new competences are necessary in relation to I4.0, thus there is a need for continuous and effective training to ensure a future skilled workforce [8]. Laboratory work is an essential component in research, education, and engineering training. However, access to laboratories can be limited due to factors such as the increase in distance learning over the last decade and restrictions caused by the Covid-19 pandemic. To address the aspects of new competences and distance studies, universities and academic research centers need to adopt new approaches in learning and teaching [9, 10]. One possible approach is to build DT of the laboratory equipment. This allows the students and researchers to perform experiments virtually and on distance. It has been noticed that there is a lack of sound real case studies of DT concepts and while data integration and synchronization methods are the main research areas and concerns of DT designers, also those techniques need more research. Most potential applications in the literature of DTs focus on industrial settings. However, in the eras of I4.0 and I5.0 we argue a worthy extended use of DTs is as a virtual tool in education and research settings, i.e., to distantly access, simulate, experiment, and study various scenarios of the system. Such applications of DTs can increase access to laboratories where otherwise access could be limited due to factors such as restrictions caused by the Covid-19 pandemic and to the growth of distance education. Thus, we conclude the ambition of this study to investigate possibilities and limitations of DT technology, and challenges and solutions for seamless transfer of production related data when applying DTs in education to conduct labs virtually. Most studies carried out on DTs focus on their industrial and commercial applications. However, there is a shortage of research addressing the use of DT technology in education [7]. The study presented here contributes to the knowledge gap in this field and we ask:

- *“What are the possibilities and limitations of applying digital twin technology in education to conduct industrial-like labs virtually?”*
- *“What challenges are there to achieve a seamless transfer between the real system and its digital twin?”*
- *“How can those challenges be addressed, solved, or avoided?”*

In the following sections background on digital twins and virtual commissioning is focused. Thereafter, the automation line case and research method are described followed by remaining sections outlining results, discussion, and conclusion.

2. Background

2.1. Digital twins

Tao, Zhang and Nee in [11] listed the most used definitions of digital twins in academia and industry and based on these definitions described the digital twin as *"a virtual representation that interacts with the physical object throughout its lifecycle and provides intelligence for evaluation, optimization, prediction"*. A digital twin consists of a physical entity, a virtual model, and connections between the physical and virtual spaces [6]. A seamless and bidirectional integration of data between the physical and digital spaces of a system is emphasized [12] and a DT has the capability of automatic data exchange and the ability to control the physical twin or be modified by that [13]. Thus, the DT can be considered the controller of the real system. A DT must be able to mimic the physical entity and be able to adapt and parameterize itself [14].

Tao et al. [11] found that there are two models of DT described: the three-dimensional and the five-dimensional. In the three-dimensional model, DT has three core components: physical space, virtual space, and connection. In addition to the core components of the three-dimensional model, the five-dimensional model has two extra components: data and service [15, 16, 17]. Further, enabling technologies of DTs have been classified into five categories based on the core components of the five-dimensional framework [11] and [17], i.e., physical entity, virtual model, service, connection, and data management.

2.2. Aspects of data fusion and integration of digital twins

Having seamless data transmission that gives real time interaction between the virtual and the real entity to monitor the health status of e.g., an automation line and proceed accordingly plays a significant role in designing DTs [18]. To design a DT with seamless integration, different kinds of communication must be considered, i.e., communication between the physical and its digital twin, between the DT with other DTs in the surrounding environment, and between the digital entity/s and domain experts, which interact and operate on the DT using applicable interfaces [14]. One time-consuming part of simulation is data collection, thus automatically collecting input data can save time [19]. DTs contain simulation models with the ability to understand the states of real systems and their components by using data from sensors and analysis, estimation, and prediction of the real time changes. The physical twin must be able to answer these changes in the simulations [20]. Challenges in DT design are acquisition and validation of input data, responsiveness of the analysis, and capability of creating a snapshot of the real system to initialize the simulation model [21]. The consistency check in a DT is a constant check for new changes in the physical space data to implement them on the virtual entity. It is argued that the data from different components in different domains must be identifiable in every data model to gain a seamless transfer of data [22]. One significant problem when developing a DT is to maintain it synchronized with the real system after commissioning [23, 24]. The critical requirement for having a DT of an automation system is to have a cross-domain synchronized system model of the physical workshop floor [23]. Synchronizing and updating the digital entity of any system is inevitable and critical so that it can mirror any state of a real system for synchronization. First, any changes in the system must be detected by constant comparing of the DT and physical system's behavior. Thus, the simulation must be constantly updated according to the changes in the physical system [24]. To make a real time simulation practical, computational time needs to be low [19]. According to [13], in development and design of DTs, data exchange must be coherent for accurate integration of external systems. The core technologies that enable the implementation of DTs are different depending on the integration level of DTs. Examples are methods such as discrete event simulation and communication protocols like OPC-UA and MQTT [13]. IoT, cloud computing and big data analysis are advances, which are critical and complementary parts of DTs [13].

2.3. Virtual commissioning

Commissioning can be defined as *"a quality-oriented process for achieving, verifying, and documenting that the performance of facilities, systems, and assemblies meets defined objectives and criteria"* [25]. With real commissioning, the system cannot be tested and validated before it is built. This often results in delays and increase the cost during the start-up phase of the system. Virtual commissioning (VC) is used mainly to overcome this problem by decreasing the time required during the commission phase [26]. VC enhances real commissioning by detecting system errors and bugs in early stages before the real commissioning is started [27]. VC is *"the simulation of a system in a virtual environment"* [28]. VC starts in the early stage of system development before the physical system is built. Using a commissioning virtual environment makes it possible to reconfigure and upgrade an existing system easily. This can be achieved with the ability to perform the VC of the system in parallel with the production and assembly processes. Modelling in VC can be divided into three sub-tasks: physical device modelling, logical device modelling and system control modelling [29]. Physical device modelling is used to transfer the physical design of the device to a digital representation. The physical device modelling includes both geometric and kinematic attributes of the system [29, 30]. The logical device modelling is used to represent the behavior of the modelled system in response to the control program [30]. System control modelling is to build the control program (PLC program) required to control the logic [29]. Figure 1 outlines the workflow of the VC technology.

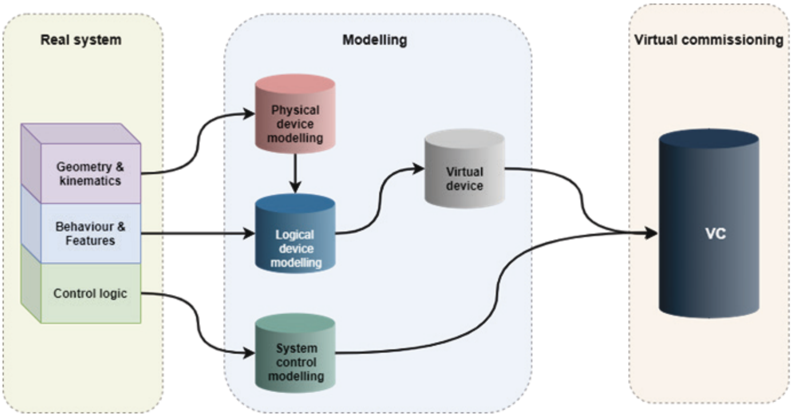

Figure 1. Virtual commissioning workflow, see [30].

Overall, this section aimed at grasping the whole concept of designing a DT and the main factors to consider, such as characteristics, architecture, virtual commissioning, and aspects of data fusion and integration.

3. Case study and methodology for research gap and case

The case focuses on building a digital model making use of DT technologies. The procedure will, for safety reason, first be tested with the users (students and researchers) PLC code on the digital model and then the code will be tested on the real system. The ambition later is to create a more advanced DT that follows its physical twin. Meaning users will command the real system with their PLC code and study its imitation on the digital system. Thus, the focus of the case lies in the initial steps towards a full DT. The research focuses a case study of an automation line, Figure 2, with full scale industrial equipment, based at a center for research and education.

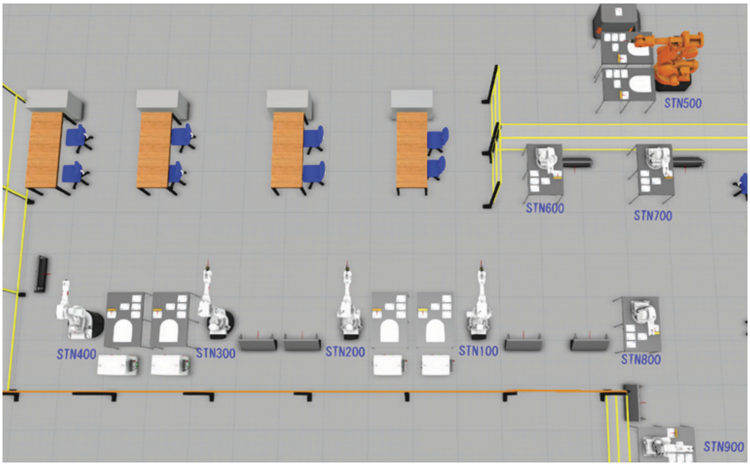

Figure 2. Automation line layout.

The line consists of nine robotic cells (STN100 – STN900) and one automated guided vehicle (AGV). The automation line uses a master/slave configuration where STN500 is the master, and the other cells (assembly stations) are slaves. The master (STN500) is an input/output station, and it is designed to perform the main control of the production line. STN500 is also used to supply and direct the assembly pallets to the different assembly stations via AGV and to store the finished products. Each station in the line is controlled by a dedicated PLC. All assembly stations and the AGV are connected to the I/O station through an OPC-UA communication server, illustrated in Figure 3.

The assembly process is performed according to the following steps: (1) a plate is placed in its position in the assembly container (2) a cylinder is then added to the plate, and (3) a screw is added to the product. All parts should have the same color as the assembly container. The production process starts by manually loading the buffers with assembly containers and parts. Every station scans its buffer storages and stores the storages content details. The I/O station supplies the line with an empty assembly container. The container is directed to the first assembly station that has the required part. A testing scenario was devised with assumptions of a reasonable quantity of parts, production cycle and assembly sequence.

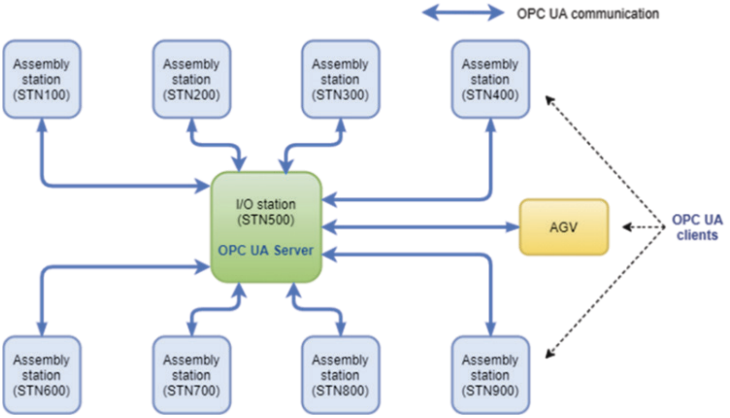

Figure 3. Layout of automation line communication.

3.1. Methodology for research gap and case

To process the collected data and convert it into the format of a DT, three key modelling types are required: physical device modelling, virtual device modelling, and system control modelling. Visual Components (VisCom) premium 4.2 was used for both physical device modelling and logical device modelling while control system modelling was performed using TwinCat3 software. The data required to build the DT can be divided into two key parts: geometrical data and behavioral data. Geometrical data include all required geometrical information such as CAD models of the key parts of the automation line. Behavioral data describe how the line component behave in response to control commands and signals. Physical device modelling is the process of transferring the physical design of a device to a digital model. The physical device modelling includes both the geometric and kinematic attributes of the modelled device. Most of the standard components could be added directly from the VisCom library, such as robots, fences, and tables. Non-standard components were modelled using AutoCAD software if they could not be modelled easily using VisCom. Logical device modelling is the process of defining the behavior of the modelled device in response to the control logic and signals. An approach to defining and controlling the behavior of the modelled component is to add a Python script to the component, which makes it possible to control the component behavior in an effective and flexible way. Adding signals and sensors to the modelled components are other examples of logical device modelling. System control modelling is the process of building the control logic (PLC program) required to control the system. System control modelling generally follow the key steps: defining and connecting the global variables, building the functions blocks and other assisting subprograms, building the main program, and designing the Graphical User Interfaces (GUIs). The key parts of the DT of the automation line reside in different software. A communication protocol is, therefore, required to allow these parts to communicate and exchange data. There are two options available to connect VisCom models and TwinCat projects. These options are Beckhoff ADS and OPC-UA. In this work, the Beckhoff ADS protocol was used because of its simplicity in both implementation and configuration for building the digital model. In the test phase the OPC-UA was used. However, the two protocols can be used interchangeably to connect the TwinCat project with the VisCom model. To conduct accurate experiments on the models and the physical twin in the laboratory at the center for research and education research, a test plan was designed according to Figure 4.

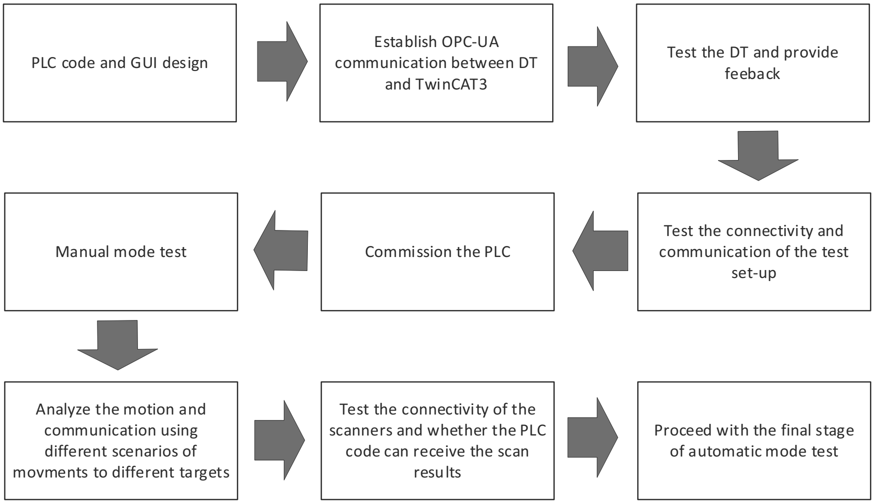

Figure 4. DT and automation line test plan routine, adopted from [32].

Upon completing the digital model, the tests on the actual system of the automation line were conducted. The connectivity was checked to see whether the communication program of the robot was functioning. Moreover, ethernet cable connections from the computer to both robots and the PLC control box was checked. Commissioning the PLC, the robots' movements were tested first using function blocks *ABBGoToTable* and *ABBGoToHome*, since the robot cells' safety need to be assured before sending the automatic mode commands to the robots [31]. Next, the assembly routine was tested in manual mode, followed by checking the scanner station results. Finally, the assembly routine was tested in automatic mode.

A PLC program was needed to design a GUI that mimics one of the stations. The GUI helps finding possible issues which the users might face while working with the DT and its physical twin. Figure 4 illustrates the first part of the tests, which was done by connecting the PLC code and the GUI written in TwinCAT3 to the digital model designed in VisCom. The OPC-UA protocol was used to provide this communication as it is the future planned communication platform of the real automation line. A complete set of assembly routine, including scanning the buffers for parts using the scanner station with the inductive sensors, picking the container from the AGV, scanning it and assemble the required parts according to their availability, was conducted.

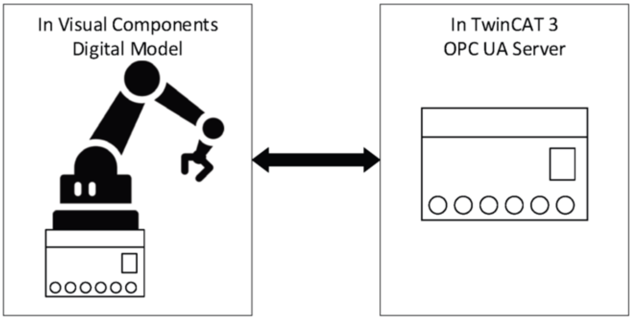

Figure 5. Connection between digital model and PLC OPC-UA server.

The designed GUI was be used to find the possible challenges in commissioning the PLC code to the real systems in the automation line. To virtually commission the PLC code, the Software-In-the-Loop approach was used since it does not require any hardware to evaluate and commission, and it gives more flexibility to its users [27]. The GUI was designed in TwinCAT3 and connected to VisCom through the OPC-UA protocol of TF6100 of TwinCAT3. The digital model was tested using the designed GUI in both manual and automatic mode. In both modes, the robot at station STN100 was successfully ordered to scan buffers and container and assemble a whole pallet with various parts. COVID-19 restrictions meant limited access to the laboratory, and therefore the entire automation line could not be prepared for testing. Thus, one station was prepared as the test station. To do so, it was needed to change the PLC code to reach the same names as the ABB Control function blocks (FB) in the Original PLC code at the station. For instance, instead of using *ABBGotoBuffer* function block to go to buffer position, it was required to change it to *ABBGoToStorage*. The testing was successful after converting the code accordingly and commanding the robot to go to different position of Home, Table, Buffer (storage), and the Scanner (sensor) station. Moreover, pick and place function blocks were successfully tested. However, conducting tests in the automatic mode of the assembly routine was not possible due to safety issues.

4. Results and discussion

This work investigated possibilities and limitations of applying DT technology in education and research to enable conducting automation labs remotely. We studied the challenges occurring, and how to address those, when aiming to achieve a seamless transfer production related data between the real system and its digital model. First the digital model performance was evaluated, for different scenarios, to investigate its function according to the provided specifications and requirements. In the first scenario, all assembly processes required to produce one product were performed completely in one assembly station. In the second scenario, the assembly processes required for every product were performed in three different assembly stations. In the third scenario, the buffers were filled randomly, and the assembly sequence required to complete one production cycle varied based on the contents of the buffers, refer to YouTube link for the third scenario simulation video [33]. Running the digital model appying the three scenarios gave similar results. The digital model was able to complete the production cycle smoothly and without issues. This was especially true when the simulation speed factor in VisCom was equal to or less than 1. With higher values of simulation speed factor, the model was mostly able to complete the production cycle. However, the model performance was not always stable, i.e., it did not run smoothly and there were time lags between some assembly processes. This behavior of the model is explicable in terms of the latency in the connection between VisCom and TwinCat. Another reason for this behavior is that increasing the simulation speed factor affects not only the simulation time of the model inside VisCom, but this is not synchronized with the running speed of the PLC program. This problem could be solved by increasing the delay time between function calls in the Python scripts in VisCom, but this solution increased the total time required to perform one production cycle. Tutorials offered by VisCom Academy are useful resources when learning the basic of modelling in VisCom, but they are probably not sufficient to acquire in-depth knowledge of the software. It was also hard to navigate and find information in the TwinCat help system, which is the main source of information for this software. Writing, testing, debugging, and troubleshooting the code that controls the digital model was hard and time consuming. Primarily, it was not easy to choose suitable languages for different tasks in TwinCat and it was difficult to debug the code in TwinCat especially the code written in the Structured Text (ST) language. The logic in this work to control the digital model is divided into two parts, the PLC program code created in TwinCat and the Python scripts code created in VisCom. These two parts are connected by a communication protocol and this structure makes the code harder to debug and troubleshoot. It was also troublesome to use some function blocks inside sub-programs written in ST language, especially timers and the function blocks that contain timers.

The next step was the testing in the physical twin and the key challenges encountered and recommendations for solutions towards a seamless transfer of production related data are:

- Names of most of the required FBs in controlling the ABB robot of the physical twin were different from their equivalent in the digital model PLC code. Thus, efforts had to be taken to understand their difference and modify the input/outputs of the FBs. Due to this complexity, it is believed that modifying the functioning code can lead to more confusion for users e.g., students. Therefore, it is recommended that the task should be changed to another level, so that their PLC code works with both the digital model and the physical twin.
- Due to having a newer build version of TwinCAT on the system used for designing the GUI than on the computer of the test setup in the automation line it was impossible to downgrade the visualization to this system. Even upgrading the computer during test to the same version was not sufficient causing problems connecting to the PLC, which meant extra effort to redesign the process. Since part of the future users, i.e., students, task will be to design a GUI, it is recommended to carry out design and experiment on the same version of TwinCAT to avoid this problem.
- A specific procedure must be followed to perform testing on the physical twin, including programming the robot with the correct Main code using the FlexPendant, while its communication program must be uploaded and working. The method will be introduced to the students, but when testing, they should be aware of the procedure and pay attention to details such as pressing the Start button or proceeding according to pop-up messages on the FlexPendant.
- The manual assembly routine was successful on the physical twin by modifying the FBs. Spending less time at the automation line, programmers can design the GUI to be able to work with both the digital model and the physical entity. One part will be used to test the automation line, which is connected to a code written by using the automation line ABB Control FBs, and the other will be used to conduct the assembly routine on the digital model to test the code. It is suggested that applying this method will support the user to conduct tests fast and accurate. An enabler switch inside each FB would give possibility to apply the same FB for digital model and physical entity, i.e., changing the value of variables with a switch or push button triggered to TRUE or FALSE.

Although the digital model of the automation line can be used directly for educational purposes, improvements may make it more practical and effective. For example, the content of the buffers of the stations is hard coded inside the VisCom model, meaning that the content of the buffers is predefined, and thus impossible to change without modifying the model. A solution could be to utilize an algorithm to randomly fill the buffers. In the real automation line, every station has its controller and thus its PLC program. However, the system control implemented in this work uses only one PLC program to control all the stations. This configuration was helpful in simplifying the implementation of the system control and its connection with the digital model. However, it can be a drawback, because with this configuration, it is hard to isolate or take control over individual stations and to assign tasks to the digital model users. This description is an example of what to consider when designing test procedures for educational purposes. The procedures need to focus on how DT technology can increase student motivation and improve learning [34] i.e., grasping an automation system, rather than encountering unnecessary obstacles. At the same time students need to get an understanding of real manufacturing processes, and thus there needs to be a balance between the learning objectives and the study efforts required. The approach can also aid distance education, especially in situations such as during the Covid-19 pandemic [35].

5. Conclusion

The work studied the application of DT technology to conduct automation labs virtually in educational settings. The DT model created consists of three key parts: a digital model of the automation line built in VisCom, a PLC-control created in the software TwinCat, and a Beckhoff ADS communication protocol that connects the digital model with the PLC program. The DT model was tested, exploring safety aspects and behavior of the real system, and efficient naming of signals and connections when designing PLC function. An assembly routine in the DT of the automation line was tested with a GUI using the OPC-UA platform both in manual and automatic mode. Due to the Covid-19 pandemic situation limiting access to the laboratory the whole automation line could not be tested at this stage. However, successful result of the thorough testing in one station confirmed the logic. The results emphasize that the design of DTs requires multi-domain expertise to understand the consequences of every single decision in the design process on every piece of equipment involved, making the process complex and time consuming to perform. Further, it is time consuming to create GUI and PLC code compatible with the automation line, and we therefore stress that when applying DT technology in educational labs it is important to design test procedures for the users such as time is spent on learning what is key to the specific subject. For example, facilitating understanding of an automation system, rather than getting stuck in technical obstacles and missing the overall picture. With clear test procedures it is beneficial in education to apply digital automation labs, especially when used in combination with physical labs. The digital models increase the accessibility of systems, which is crucial when access to the physical systems is restricted. Further, virtual automation labs are useful tools for testing and debugging the system control programs before they are uploaded to the real controllers, and what-if scenarios for optimization can be evaluated. The study outlines an educational application of DT technology, though results should be interesting and valuable in other settings, such as within the manufacturing industry. The basis of the work presented in this paper is the digital twin technology, an emerging technology considered a part of Cyber-Physical Systems (CPS). Here, the use of such DT and CPS approaches is stressed for educational and research laboratories, but in addition to this, the work contributes to other research areas such as automation and virtual commissioning towards smart manufacturing. Digital twin technology and simulation are considered enabling technologies for supporting the concept of I5.0, highlighting the human-centric aspects of moving forward with I4.0 [3]. I5.0 has evolved to emphasize improved interaction between human and machines and consider the critical thinking of human resources [2]. If application of DTs and related technologies are increasing as predicted [3, 4] then use of such approaches needs to be included in educational curricula as realistic laboratory applications as well as theoretically understood.

Our approach can be extended to consider the difference between the two architectures (Beckhoff ADS and OPC-UA) and to evaluate their implementation using the same PLC program and VisCom model, to choose the architecture with the highest performance and least time delay. Moreover, the next part is to implement the method in education and evaluate the case on groups of students. Further, the intention is to create a more advanced DT that incorporates intelligence for evaluation, optimization, and predication of its physical twin.

References

[1] Oztemel E, Gursev S. Literature review of Industry 4.0 and related technologies. Journal of Intelligent Manufacturing. 2020 31:127–182, https://doi.org/10.1007/s10845-018-1433-8.

[2] Javid M, Haleem A. Critical components of Industry 5.0 Towards a successful adoption in field of manufacturing. Journal of Integration and Management. 2020 3:327-348, https://doi.org/10.1142/S2424862220500141.

[3] European Commission. Industry 5.0 Towards a sustainable, human-centric and resilient European industry. 2021, R&I Paper Series Policy Brief, Luxembourg: Publications Office of the European Union, ISBN 978-92-76-22048-0.

[4] European Commission, Directorate-General for Research and Innovation. Müller, J. Enabling Technologies for Industry 5.0: results of a workshop with Europe's technology leaders. Publications Office. 2020, https://data.europa.eu/doi/10.2777/082634.

[5] Parmar R, Leiponen A, Tomas, LD. Building an organizational digital twin. Business Horizons. 2020 63(6):725-736.

[6] Agalianos K, Ponis ST, Aretoulaki E, Plakas G, Efthymiou O. Discrete Event Simulation and Digital Twins: Review and Challenges for Logistics. Procedia Manufacturing. 2020 51:1636–1641.

[7] Lu Y, Liu C, Wang KI-K, Huang H, Xu X. Digital twin-driven smart manufacturing: Connotation, reference model, applications and research issues. Robotics and Computer-Integrated Manufacturing. 2019 61, https://doi.org/10.1016/j.rcim.2019.101837.

[8] Maddikunta PKR, Pham Q-V, Prabadevi B, Deepa N, Kapal D, Gadekallu TR, Ruby R, Liyange M. Industry 5.0: A survey on enabling technologies and potential applications. Journal of Industrial Information Integration. 2021, https://doi.org/10.1016/j.jii.2021.100257.

[9] Hattinger M, Eriksson K. Mind the Gap: A Collaborative Competence E-learning Model Evolving Between University and Industry. Journal of Strategic Innovation and Sustainability. 2020 15(5):1-15.

[10] Eriksson K, Bränneby E, Hagelin M. An educational model for competence development within simulation and technologies for industry 4.0. In: Kim S, Feng B, Smith K, Masoud S, Zheng Z, Szabo C, Loper M, ediotors. Proceedings of the Winter Simulation Conference, 2021 Dec 15-17, Virtual Conference.

[11] Tao F, Zhang M, Nee A. Digital Twin Driven Smart Manufacturing. 2019, London: Academic Press.

[12] Fuller A, Fan Z, Day C, Barlow C. Digital Twin: Enabling Technologies. IEEE Access. 2020 8:108952-108971.

[13] Kritzinger W, Karner M, Traar G, Henjes J, Sihn W. Digital Twin in manufacturing: A categorical literature review and classification. IFAC-Pap. 2018 51(11):1016–1022, https://doi:10.1016/j.ifacol.2018.08.474.

[14] Barricelli BR, Casiraghi E, and Fogli D. A Survey on Digital Twin: Definitions, Characteristics, Applications, and Design Implications. IEEE Access. 2019 7: 167653–167671, https://doi:10.1109/ACCESS.2019.2953499.

[15] Wu C, Zhou Y, Pessôa MVP, Peng Q, Tan R. Conceptual digital twin modeling based on an integrated five-dimensional framework and TRIZ function model. Journal of Manufacturing Systems. 2021 58:79-93.

[16] Sun L, Pei A, Qi X, Cao S, Yang R, Liu X. Dynamic Analysis of Digital Twin System Based on Five-Dimensional Model. Journal of Physics: Conference Series. 2020.

[17] Qi Q, Tao F, Hu T, Answer N, Liu A, Wei Y, Wang L, Nee AYC. Enabling technologies and tools for digital twin. Journal of Manufacturing Systems. 2021 58:3-21.

[18] Wu P, Qi M, Gao L, Zou W, Miao Q, Liu L. Research on the Virtual Reality Synchronization of Workshop Digital Twin. IEEE 8th Joint International Information Technology and Artificial Intelligence Conference (ITAIC). 2019 May 24-26; Chongqing, China:IEEE p. 875–879, https://doi:10.1109/ITAIC.2019.8785552.

[19] Lugaresi G, Matta A. Real-time simulation in manufacturing systems: Challenges and research directions. In: Rabe M, Juan AA, Mustafee N, Skoogh A, Jain S, Johansson B. Proceedings of the Winter Simulation Conference; 2018 Dec; Gothenburg, Sweden; Dec. p. 3319–3330, https//doi:10.1109/WSC.2018.8632542.

[20] Qi Q, Tao F. Digital Twin and Big Data Towards Smart Manufacturing and Industry 4.0: 360 Degree Comparison. *IEEE Access*. 2018 6:3585–3593.

[21] Liu Z, Meyendorf N, Mrad N. The role of data fusion in predictive maintenance using digital twin. AIP Conference Proceedings 1949, Provo, Utah, USA, 2018, p. 020023. doi: 10.1063/1.5031520.

[22] Talkhestani BA, Jazdi N, Schlögl W, Weyrich M. A concept in synchronization of virtual production system with real factory based on anchor-point method. Procedia CIRP. 2018 67:13–17.

[23] Talkhestani BA, Braun D, Schloegl W, Weyrich M. Qualitative and quantitative evaluation of reconfiguring an automation system using Digital Twin. Procedia CIRP. 2020 93:268–273.

[24] Zipper H, Diedrich C. Synchronization of Industrial Plant and Digital Twin. In 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA); 2019 Sep 10-13; Zaragoza, Spain: IEEE; p. 1678–1681. https://doi:10.1109/ETFA.2019.8868994.

[25] The Commissioning Process; ASHRAE Guideline; 0-2005, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2005. ISSN 1049-894X.

[26] Hoffmann P, Schumann R, Maksoud TM, Premier GC. Virtual commissioning of manufacturing systems: A review and new approaches for simplification. In European Conference on Modelling and Simulation; 2010 Jun 1-4; Kuala Lumpur, Malaysia, 2010 p. 175-185.

[27] Lechler T, Fischer E, Metzner M, Mayr A, Franke J. Virtual Commissioning – Scientific review and exploratory use cases in advanced production systems. Procedia CIRP. 2019 81:1125–1130.

[28] Vermaak H, Niemann J. Virtual commissioning: A tool to ensure effective system integration. In IEEE International Workshop; Donostia, San Sebastian, Spain, 2017.

[29] Mortensen ST. Identify - Quantify - Obtain: Qualifications for virtual commissioning. 2019. PhD Thesis. Aalborg, Denmark: Aalborg University Press.

[30] Lee CG, Park SC. Survey on the virtual commissioning of manufacturing systems. Journal of Computational Design and Engineering. 2014 1(3):213–222.

[31] Singel R. Industrial Control Systems Killed Once and Will Again, Experts Warn. Wired. Accessed: Oct 8th, 2021. [Online]. Available: https://www.wired.com/2008/04/industrial-cont/

[32] Guignard A, Faure J-M. A conformance relation for model-based testing of PLC. In 12th IFAC/IEEE Workshop on Discrete Event Systems. 2014 May 14-16; Cachan, France. IFAC Proc. 47(2):412–419.

[33] Virtual Automation Line. YouTube Video. Accessed: Oct 8th 2021. [Online]. Available: https://youtu.be/q2IQgSsj6mU

[34] Liljaniemi A, Paavilainen H. Using digital twin technology in engineering education – Course concepts to explore benefits and barriers. Open Engineering 2020, doi/10.1515/eng-2020-0040.

[35] Sepasgozar SME. Digital twin and web-based virtual gaming technologies for online education: A case of construction management and engineering. Applied Sciences 2020, 10, doi.org/10.3390/app10134678.