Research Article

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Using Digital Twin Technology in Engineering Education – Course Concept to Explore Benefits and Barriers

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Abstract: Digital Twin (DT) technology is an essential technology related to the Industry 4.0. In engineering education, it is important that the curricula are kept up-to-date. By adopting new digital technologies, such as DT, we can provide new knowledge for students, teachers, and companies. The main aim of this research was to create a course concept to research benefits and barriers of DT technology in engineering education. The research confirmed earlier findings concerning digitalization in engineering education. DT technology can increase motivation for studying and improve learning when applied correctly.

Keywords: Digital Twin, Digital Shadow, Industry 4.0, Engineering Education, Virtual Learning Environment

1 Introduction

Digital twin technology is one of the main technologies related to Industry 4.0. It is vital in engineering education that the curricula and the contents of the education are kept up-to-date including the educational environments and know-how of the teachers.

Students, teachers, and companies can benefit from utilizing new digital technologies, such as, DT tools. This can have an impact on the employment of the students and competitiveness of the companies [1].

The main aim of this research was to create a course concept to research digital twin technology in engineering education and to adopt the technology in education. The research also aimed to explore the benefits and barriers of DT technology, to evaluate its inclusion into the curricula and its maturity level, as well as to find the best way to adopt the technology.

1.1 Scientific Contribution

To summarize our contribution, this research introduces a new DT based concept for teaching. Further, this paper closes the toolchain loop by testing and evaluating industrially used DT tools. Continuous feedback is important while developing new software products. Finally, our research was experimented with BSc students. It describes the best practices for implementing DT technology in engineering education.

2 Concept of Twins

2.1 History of the Twins

The phrase *digital twin* is commonly used in industry and the scientific community; however, an exact definition of this concept is currently lacking. The concept of using "twins" originates from NASA's Apollo program for which at least two identical space vehicles were built, allowing the engineers to mirror the conditions of the space vehicle during the mission, the vehicle remaining on earth being called the twin [2, 3].

The present technology known as Digital Twin (DT) was first introduced in 2002 by Michael Grieves. DT definitions in prior research emphasize that each system consists of two systems, the physical system and a virtual system, which contains all of the information about the physical system [4–6]. Siemens defines it as follows: *"A digital twin is a virtual representation of a physical product or process, used to understand and predict the physical counterpart's performance characteristics. Digital twins are used throughout the product lifecycle to simulate, predict, and optimize the product and production system before investing in physical prototypes and assets"* [7].

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2.2 Digital Twin Technology

Digital twin technology examples are already in use in manufacturing and some other sectors. The tools to work with twins can be wide product lifecycle management (PLM) packages or more narrow products similar to Visual Components for a specific purpose. The benefits of DT technology include cost cutting, reduced time-to-market, and predictive maintenance. Earlier research classifies digital twins into three sub-categories [8, 9]:

1. Digital Model, which is a digital representation of an existing or planned physical object, with no automated data exchange between the physical-digital objects.
2. Digital Shadow, which exists as an automated one-way data flow between existing physical-digital objects.
3. Digital Twin, in which the data flows between the physical-digital objects which are fully integrated in both directions.

3 Using Digital Twin Technology in the Course “Simulation in Control System Design”

3.1 Methods

The main research method was action research, which was used to conduct the observations, recorded by taking notes, in order words, the KJ technique. The research was planned in three cycles between 2016 and 2018. The first cycle involved creating the course concept and the second cycle was based on observations made during the first. The third cycle was similar to the first and second cycles but with the necessary modifications applied. Furthermore, after the third cycle, the students answered a survey concerning the application of digitalization and DT technology in the course. Furthermore, the statistical data of the DT courses were analyzed and compared with other courses.

The digitalization inquiry conducted was the same inquiry used in the Digitalization in Professional Education research [10]. In addition to the inquiry, a set of Digital Twin related questions were added. The same inquiry was used to be able the compare the results.

3.1.1 KJ-technique

KJ-technique (also sometimes referred to as an “affinity diagram” (Figure 1)) is named after its inventor, Jiro Kawakita [11]. The technique is one form of action research. It allows users to categorize their observations into classes, to prioritize them, and finally, to decide which activities should be next performed. The method was applied in the following way:

Step 1: Two Focus Questions were determined, Benefits and Barriers.
Step 2: Teachers implemented their ongoing observations throughout the course.
Step 3: After the course, the observations were written onto Sticky Notes.
Step 4: Sticky Notes were added to the wall.
Step 5: Similar items were grouped.
Step 6: Each group was named according to the category it seemed to represent.
Step 7: The groups with the most notes were then selected as being the most significant, then in order to reduce the number of categories, the teachers placed the remaining notes into the larger categories.
Step 8: Finally, groups were ranked and prioritized. The next course cycle was planned based on observations made, grouped, ranked, and prioritized.

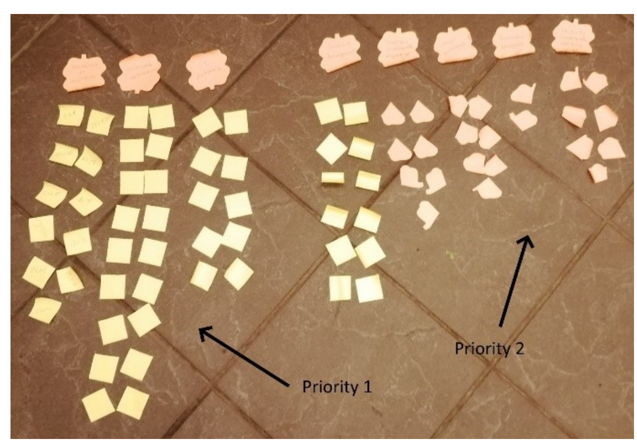

Figure 1: Affinity diagramming for sorting findings [12]

3.2 Course Description and Participations

To adopt and research digital twin technology, a course named Simulation in Control System Design was chosen. This course is part of the studies of machine automation, which is one of the three majors within the mechanical engineering department.

3.2.1 Course Description

The learning outcomes of the course were:

- On completion of the course, the student will be familiar with the possibilities of simulations and able to create useful simulation models to test product behavior.
- The student will be able to use simulation models to develop and test the steering and control algorithms.

The prerequisites and co-requisites demanded a knowledge of 3D modeling and CAE.

The recommended optional programme components:

- The student advisor will recommend optional programme components for each student based on their individual study plan.

The course content covers:

- Advantages of simulations.
- Principles of creating a simulation model, as well as its verification and testing.
- Various simulation environments.
- Simulation cases in various applications.

3.2.2 Participations

The research was planned in three cycles. The first cycle was implemented in 2016, and consisted of creating the course concept, developing and implementing the action plan, gathering and analyzing the data, identifying the problems, and evaluation. The results were used to plan the second cycle. The participants of this first cycle were 21 students and two teachers. The second cycle was implemented in 2017, for this cycle some minor modifications were made for the concept. The participants of this second cycle were 28 students and two teachers. The third and final cycle was implemented in 2018; for this cycle, the students answered a survey after the course concerning digitalization and digital twin technology. The participants of this third cycle were 42 students and two teachers.

As is typical in action research, the teachers also were the researchers of the study. In this study, the researchers were full participants due to being permanent science and technology teachers at the university.

3.3 Course Concept to Research and Adopt DT Technology

This research started in spring 2016. The machine automation major had new curricula and a new upcoming course: Simulation in Control System Design. During 2016, different DT pieces of software were tested and compared. Tools that were tested: NX Mechatronics Concept Designer (MCD), Mevea and Visual Components. NX MCD was chosen to be used in the first course implementation in autumn 2016.

NX MCD (Figure 2) is part of the Siemens PLM tools. It is a physics-based modeling and simulation tool. One feature of MCD is its ability to validate that the product designed works properly prior to it being built. This validation is enabled by the re-use library, from which a user can quickly add data to the functional model. This data includes joints, motion, sensors, actuators, collision behavior, and other kinematic and dynamic properties for each component. This allows a physics-based, interactive simulation to verify machine operation [7]. With MCD, it is also possible to implement a virtual commissioning of a functional model.

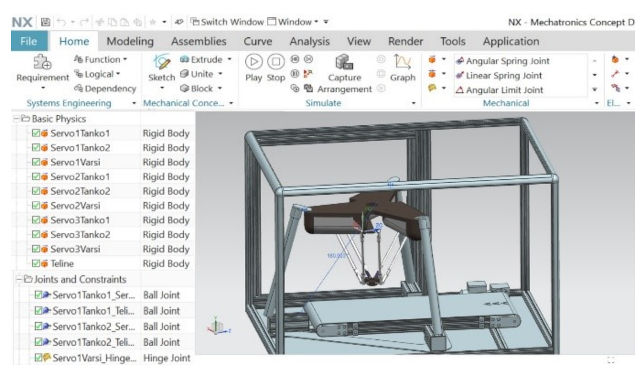

Figure 2: NX Mechatronics Concept Designer

A new concept was created for this course. The study module is divided into two parts, Part 1 is a theory part and Part 2 a hands on project, each part lasting 8 weeks. During the first part, the students examine the digital twin software tools and then work on individual exercises. After the first period, students are divided into project groups and a large digital twin project is distributed to the groups. The project has four parts: designing a 3D model of a mechatronics equipment, converting the 3D model into the digital twin with the NX Mechatronics Concept Designer, designing a PLC program for the equipment, and linking the PLC with a digital twin through OPC. Finally, when the projects are ready, the groups demonstrate the projects to the teachers and perform a virtual commissioning. The topics of the projects included mechatronic equipment, such as

- Delta, Scara and ABB YuMi robots
- Conveyor belt, XYZ crane
- Darts thrower, turntable
- Smart Factory

3.3.1 Designing a 3D Model

In the project, the 3D model is designed with the Catia CAD tool. Students are free to use other CAD tools as well, for example, SolidWorks or NX. The model can be designed completely from the beginning or available 3D models can as well be used from the manufacturer catalogs. Designed models need to match the actual mechatronics equipment. 3D models are transferred to NX MCD in stp-format. One machine used as a project subject was a Delta robot, which is used in various mechatronics courses (Figure 3). In addition to actual existing equipment, students have an opportunity to use imaginational equipment, such as, the ABB FlexPicker (Figure 4).

3.3.2 Converting the 3D Model into Digital Twin

The second part of the project is to convert the 3D model into a simulation model, in other words, the first phase of a Digital Twin. For this purpose, the 3D models must be imported into NX MCD. First, the necessary rigid and collision bodies are defined. After defining of the bodies, the necessary joints are configured to enable movements (Figure 5). Finally, sensors and controls are defined for the physics simulation. Sensors (Figure 6) are needed to monitor the physics simulation and to connect the sensor elements to PLC inputs to implement a virtual commissioning. Controls (Figure 7) are needed to control the simulation and to connect the control elements to PLC outputs. The designed DT model can be tested by adding the sensors and controls to a so-called inspector or connecting it to a simulation or real PLC.

3.3.3 PLC Programming

The third part of the project is designing a PLC program for the equipment. For this, a requirement specification is given to the students. The PLC program should include the following parts:

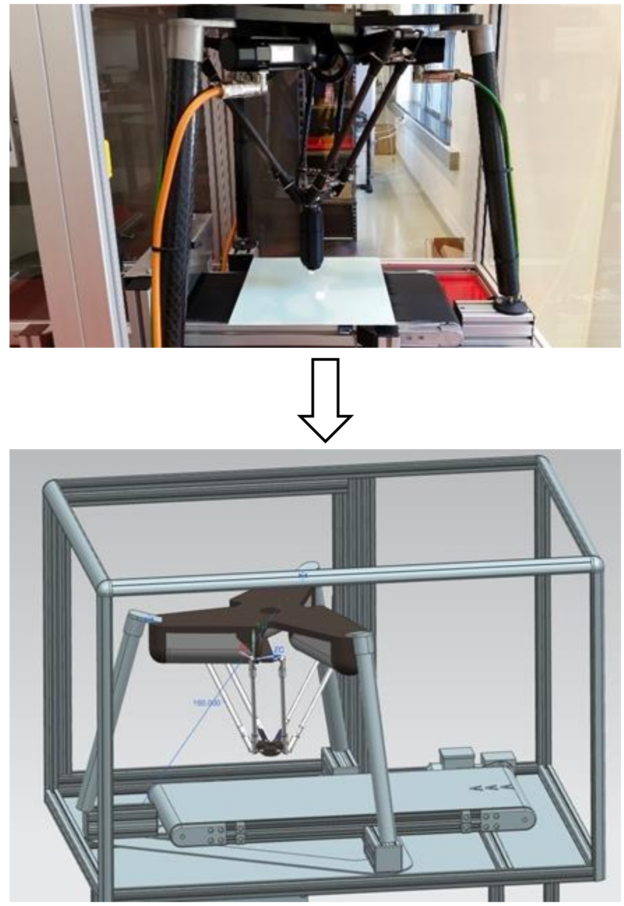

Figure 3: Delta robot in mechatronics lab and 3D model

Figure 4: ABB Flexpicker and 3D model

- Automatic control for the equipment
- Manual control for the devices
- Alarms
- Interface to NX MCD

In machine automation, Siemens TIA, Beckhoff TwinCAT, and Codesys PLC systems are the most commonly used; therefore, the project groups can choose from among these systems. If students wish, they can also use some other systems such as Raspberry Pi or Arduino.

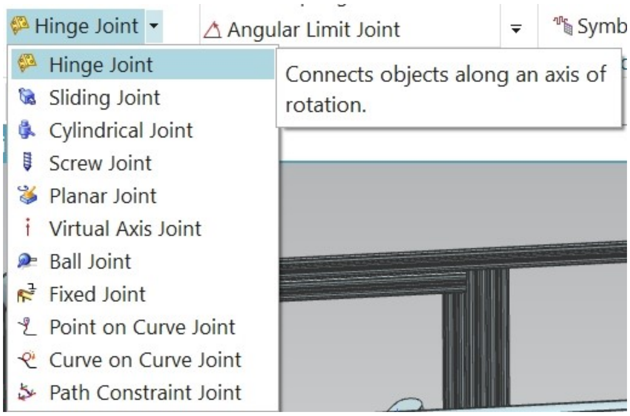

Figure 5: Available joint types

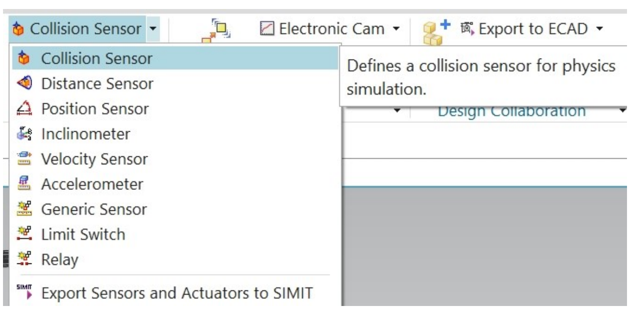

Figure 6: Different sensors

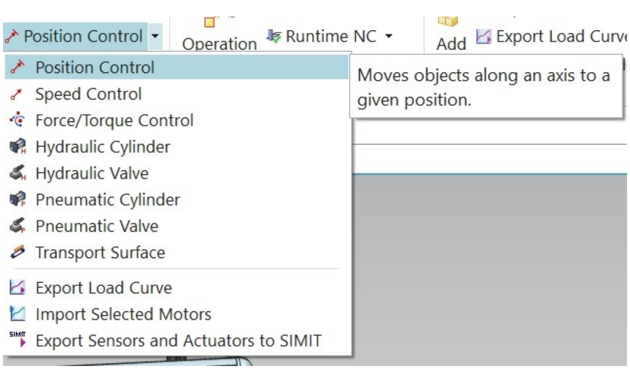

Figure 7: Different control elements

3.3.4 Virtual Commissioning

The final and fourth part of the project is to perform a virtual commissioning. Project groups connect the designed PLC programs with NX MCD models. For building the interface, NX MCD provides different technologies such as OPC DA, OPC UA, and Profinet (Figure 8).

Virtual commissioning can be implemented as software-in-the-loop simulation (SIL) or as hardware-in-the-loop simulation (HIL). In the SIL simulation, the PLC program is simulated with a PLC simulator in the PC. In the HIL simulation, the PLC program is run and tested in a real PLC connected to a PC with the NX MCD model (Figure 9).

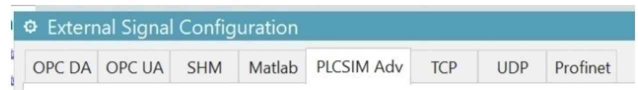

Figure 8: Different interfaces

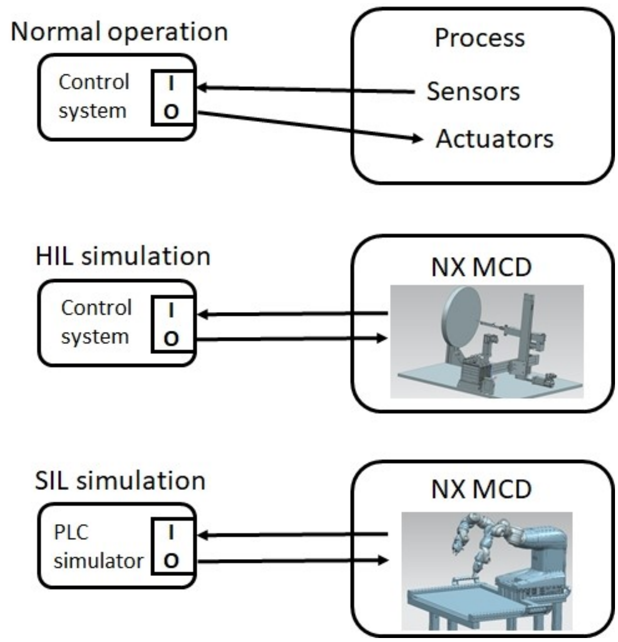

Figure 9: Normal operation, HIL and SIL simulation

4 Results and Discussion

The present study confirmed the earlier findings concerning digitalization in engineering education. Digital tools and DT technology can increase study motivation, students' own responsibility for learning, as well as improve learning. However, digitalization as a form of learning is sometimes overly emphasized in lieu of a more personal encounter with the teacher and other learners. Compared with other machine automation courses, the yield and first time through were at the same level. DT technology did not increase or decrease these key indicators. The main benefits of the technology were the development of expertise and increased motivation for studying. The main barriers were IT problems, lack of resources, and teachers' inadequate expertise.

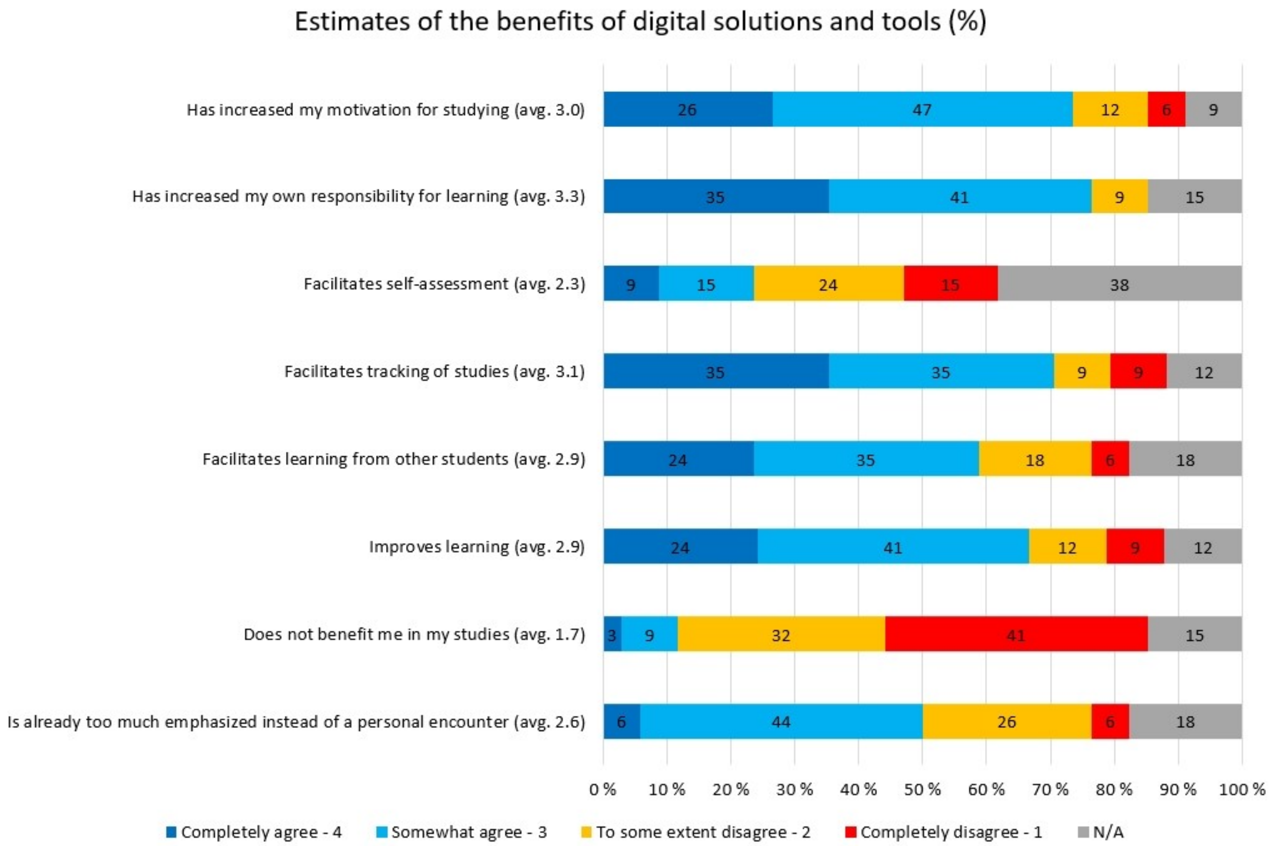

Figure 10: Replies to the question on 'Estimates of the benefits of digital solutions and tools'

4.1 Digitalization Inquiry

After the third cycle, an inquiry was carried out for the third cycle students. Answering percentage was 92%. The inquiry was the same as used in the Digitalization in Professional Education research [10]. In addition, a set of Digital Twin questions were added.

The first part of the inquiry covered digitalization in general. Based on first part, students identified the benefits of the digitalization in the following way (Figure 10):

- Has increased my motivation for studying
- Has increased my own responsibility for learning
- Facilitates tracking of studies
- Facilitates learning from other students
- Improves learning

Compared to previous digitalization research such as Digitalization in Professional Education (DiPE), the results were similar [10, 13]. In DiPE, the average was 2.5 for two of the questions 'has increased my motivation for studying' and 'improves learning'. In this study, the average was 3.0 for these questions, from this point of view, machine automation students perceive the digitalization very positively. Although they recognize that digitalization is already sometimes excessively emphasized instead of a personal encounter. From a teacher's perspective, it is not sufficient that a digital task such as DT project is set, one must provide for technical support and assist, preferably 24/7.

The second part of the inquiry covered DT technology. Based on this part, students identified the benefits of DT technology in the following way (Figure 11):

- I think the course will be useful to me in the future
- Digital Twin technology has increased my motivation for studying
- Digital Twin technology has made learning easier with the course
- Digital Twin know-how makes my job easier and I feel that there is a need for this expertise in working life

Compared to part one, DT technology was recognized even more positively than digitalization overall. The technology was not familiar to the students before the course. The IT environments did not receive that positive feedback, probably due to the problems encountered while accomplishing the project. In order to facilitate the students'

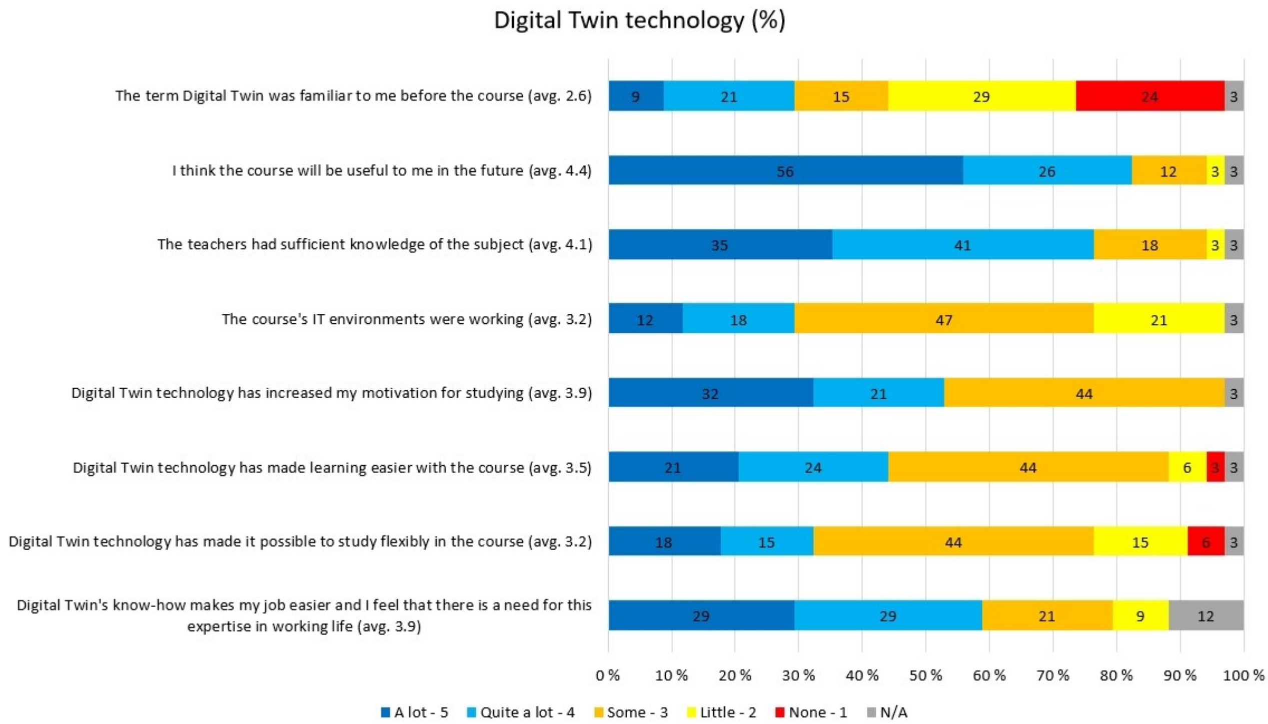

Figure 11: Replies to the question on 'Digital Twin technology'

learning and improve accessibility, the DT tools and environments could be placed into a virtual server, which would increase flexibility.

4.2 Action Research

An action research method called KJ-technique was used to observe recognitions for two questions, benefits and barriers of the DT technology in education. After each cycle, the observations were classified and prioritized. This information was used to further develop the course concept. Finally, after all three cycles, the all observations were classified and prioritized once more and analyzed to resolve the benefits and barriers of DT technology in education. The conclusions of this action research were the following groups.

Priority 1 groups:

- Development of expertise
- Increased motivation for studying
- IT problems

Priority 2 groups:

- Constant course development
- Ensuring the resources
- Other problems and barriers
- Teachers inadequate expertise
- Students inadequate starting level

One clear benefit was the development of expertise related to DT technology. Both students and teachers gained new knowledge and in some cases, this resulted to find employment. The other explicit benefit was increased motivation for studying. Students perceived the DT technology beneficial for their future careers.

When adopting DT technology in education, one possible barrier is potentially the IT problems. During the research and when using the NX MCD, students had problems with the OPC interface due to different OPC products in the same PC. Furthermore, some conflicts were faced due to Windows updates. Thus, one must pay attention keeping software up-to-date and prepare for possible problems.

Other observations were that the technology is evolving fast and thus constant course development is necessary. DT tools and software are quite complex tools and learning curve might be high, therefore, ensuring resources is vital. Working with new technology and applying it in this way means that teachers do not necessarily have answers for all the questions immediately.

Table 1: Machine automation courses 2016-2018

Time period 2016-2018, research cycles 1-3	Students
Simulation in control system design	91
Mechatronics	45
Control and servo systems	82
PLC programming and network system basics	89
Sensors and machine vision	94
Hydraulic systems	101
Automation project	43
Embedded system and programming	51
Total number of students *Without Simulation in control system design*	**505**
Total number of students	**596**

Table 2: Key indicators

Time period 2016-2018, research cycles 1-3	Yield	Avg.	FTT
Simulation in control system design	92.31%	3.63	92.31%
Mechatronics	84.44%	3.85	82.22%
Control and servo systems	92.68%	3.54	91.46%
PLC programming and network system basics	92.13%	3.92	91.01%
Sensors and machine vision	91.49%	3.49	91.49%
Hydraulic systems	82.18%	3.60	81.19%
Automation project	95.35%	3.61	93.02%
Embedded system and programming	94.12%	3.83	92.16%
Without Simulation and programming	**89.9%**	**3.67**	**88.7%**

4.3 Statistical Data

The statistical data of the DT courses were analyzed and compared with other machine automation courses in Metropolia (Table 1). In the other courses, the teachers were the same and students correspondingly. The key indicators used were (Table 2):

- Yield - the passing percentage
- FTT - First Time Through - the percentage of how many students pass the course on the first try
- Average grade - courses are scored from 0 to 5, 0 means failed and 5 is the highest score

Yield for all three cycles was 92%, FTT 92% and average grade 3.6/5. Compared with other courses, these key indicators were at the same level. DT technology did not appear to have any significant effect. On the other hand, professional software tools are also used in other machine automation courses.

5 Conclusions and Future Work

The aim of this research was to create a course concept to research digital twin technology in engineering education and to adopt the technology in education. As a result of this research, a digital twin course was successfully created to confirm the concept. The current setup still has limitations and needs to be further developed. The benefits and barriers were analyzed and researched. Obviously, many digital tool already exist which are commonly called DT tools; the strictest DT definition [8] was: Digital Twin, the data flows between the physical-digital objects are fully integrated in both directions. According to the definition, most of the current tools are so called, Digital Model and Digital Shadow tools. To achieve and to be able to design a true Digital Twin, the technology needs to be developed and researched further.

When using the tools as separate design tools, the operation was stable, but when digital twins were connected with PLCs, many problems were confronted with OPC version and other malfunction issues. To use and exploit the created twins and the technology in other courses, one alternative would be to create a virtual mechatronic lab [1]. This would enable the using of the twins in other courses and further research of the benefits.

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