PROJECT-BASED LEARNING IN ENGINEERING EDUCATION – DEVELOPING DIGITAL TWINS IN A CASE STUDY

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ABSTRACT

The current engineering environment demands for an increasing level of interdisciplinarity, innovation, creativity and cross-domain thinking as well as the consideration of sustainability aspects. New concepts, such as Digital Twins and complex product systems lead to the need for integrated product development approaches and new methods that put the user perspective in focus. This also needs to be an integral part in today's teaching concepts of the next generation of engineers.

At the Department of Industrial Information Technology of the Technical University of Berlin, a case study was conducted by applying a concept of project-based learning in the engineering domain to address these challenges. In this paper, the case study as well as the method and its validation are presented. Students from different engineering disciplines had the task of developing virtual and physical prototypes for a sustainable, complex product system with a digital twin and respective sustainable business models. Within a structured survey, the teaching concept and the applied method were validated and lessons learned as well as further improvement measures are derived.

Keywords: Education, Integrated product development, PBL, Digital Twins, Sustainability

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1 INTRODUCTION

Project-based learning (PBL) represents a core university didactic concept for engineering education in order to equip students with important key competences between technical knowledge and engineering/project execution knowledge for work practice (Frank, et al., 2003). Courses in the PBL format at the Department of Industrial Information Technology of the TU Berlin are characterised by the fact that interdisciplinary student project teams are given the task of designing and developing a mechatronic product with a Digital Twin (DT). The additional challenge here is the sustainable development and self-management of the teams. Due to its decidedly practical orientation, the module is characterised by a high degree of direct interaction, both between the students and with the lecturers. Due to the COVID-19 pandemic, a hybrid teaching concept was developed in the winter semester 20/21 in order to be able to offer the more than 50 students a module that is close to the working world.

Both, the engineering/project interface between virtual and analogue interaction was considered, and the task itself was divided into physical and virtual design tasks. This meant that students and lecturers were faced with the challenge of not only adapting traditional and tried-and-tested procedures to the pandemic-related circumstances, but also rethinking them for the future.

2 THEORETICAL BACKGROUND

2.1 Learning method

In recent years, a paradigm shift from teacher-centred to student-centred learning has been observed in the teaching methods used (Shin, 2018). Student-centred teaching methods include PBL, which also entails problem-based learning. PBL not only provides students with knowledge, but also improves their problem-solving skills, critical and creative abilities, lifelong learning, communication skills, teamwork, adaptation to change and self-assessment (Anazifa, 2017).

Particularly in engineering, most work is not done individually, but in development teams. Their knowledge is becoming more and more complex due to increasing requirements and new technologies. However, the knowledge is generated, and sometimes applied, by individuals in the groups. As a result, successful product development teams must be able to share and negotiate increasingly heterogeneous knowledge (Wang et al., 2019). To teach these necessary skills and increase students' professional maturity with problem-based learning (Strobel and Barneveld, 2009), PBL, which involves students in meaningful projects and the development of real products, has become a central element of engineering education (Brundiers and Wiek, 2013; Kolmos 2017).

As a result, several frameworks have come to the fore (Edström and Kolmos, 2014) and recent publications have discussed the issues associated with PBL in engineering education (Chen et al., 2020) and the current state of PBL in Europe (Bauters et al., 2020). Other studies have focused on teachers' perspectives and experiences of PBL (Vesikivi et al., 2019; Mitchell and Rogers, 2020) and students' perspectives on PBL in relation to specific issues such as sustainability (Servant-Miklos et al., 2020; Alves et al., 2017), collaboration (Du et al., 2019) and motivation (López-Fernández et al., 2019). To our knowledge, there has been no research on what graduate students actually do in project work to acquire knowledge (Mörike et al 2021).

A total of six characteristics of PBL are identified in the literature. There is a driving question as well as a focus on set learning goals, participation in educational activities, collaboration between learners, the use of assistive technologies and the creation of tangible artefacts (Krajcik & Shin, 2014).

In PBL, the teaching staff is not only a "knowledge broker" or "fact provider", but rather a mentor, helper and facilitator of learning (Frank, et al., 2003). In this respect, PBL differs from other learner-centred principles by creating artefacts that solve authentic problems (Guo, et al., 2020).

2.2 Digital twins

For the courses in the year of 2019/2020 and 2020/2021 the specific topic of DTs as integrated. DTs originally were defined within aerospace applications and focused on simulation tasks (Boschert and Rosen, 2016) stretching over several lifecycle phases. The definition, which was used for the development task within the project has been published by Stark and Damerau: “A Digital Twin is a digital representation of an active unique product (real device, object, machine, service or intangible asset) or unique product service system (a system consisting of a product and a related service) that

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comprises its selected characteristics, properties, conditions and behaviors by means of models, information and data within a single or even across multiple life cycle phases." (Stark and Damerau, 2019) Studies have showed, that the concept of DT is highly relevant from industrial application perspective (Riedelsheimer et al. 2020), which also pushes the need for the integration in teaching.
The development of DTs is usually either derived from the development of mechatronic products or software (see Riedelsheimer et al., 2021). Within this course, the methodology to develop DTs developed by Riedelsheimer et al. was applied by the student teams in an adapted version to the use case. The classical V-Model (VDI 2221 resp. VDI 2206) has been extended with an interconnected stream of development steps, which is intertwined with the mechatronic product and service development. Also, the consideration of the products and the DTs environmental impact by executing an LCA (DIN EN ISO 14040, 2019) has been integrated. For the development of DT, additional roles are necessary in the form of a sustainability expert and DT expert, who should be equipped with the skillset of systems engineering, data engineering and software as well as IT-infrastructure understanding. Also, the competencies of mechatronics and service development are of increasing importance.

3 USE CASE

At the Department of Industrial Information Technology (IIT), a PBL engineering project is conducted every year. In recent years, new challenges such as remote teamwork, online seminars or exams were added due to the pandemic. This led to the need to switch to a hybrid learning concept with digital media.
The aim of the course is to teach students interdisciplinary project work that is as close to industrial practise as possible. In addition to the learning objectives of technical and methodological skills such as design thinking, DT development and sustainable engineering, the students should learn soft skills such as communication, team leadership, structured working methods, presenting and hybrid collaboration.

3.1 Structure of the semester project

The project-seminar in this composition has already been held at the department since October 2017, i.e. for five years and has been repeatedly adapted over the years to current events as well as to the learning needs of the students and didactic findings of the teachers. It is specifically designed to train not only concrete engineering knowledge but also the students' ability to integrate knowledge and to promote cooperation in multidisciplinary teams. A project team consists of 8-9 students and goes through the entire product development process from the initial idea to the implementation of a real prototype. This is done similarly to an industry-typical approach. The members of the project teams have different technical backgrounds and are enrolled in one of two modules. Both modules are part of the engineering master's programmes at TU Berlin and have either a management focus (Development and Management of Digital Product Creation Processes (EMP)) or a development focus (Applications of Industrial Information Technology (AIIT)). Combining these two modules in a single PBL setup (Fig. 1) gives students the opportunity to experience the challenges of different tasks, interests and priorities in real product development projects in industry. The projects we studied for this paper ran from October 2021 to February 2022 (winter semester 2021/22). A total of 54 students (20 from the EMP module, 34 from the AIIT module) formed 6 project teams (see Figure 1).

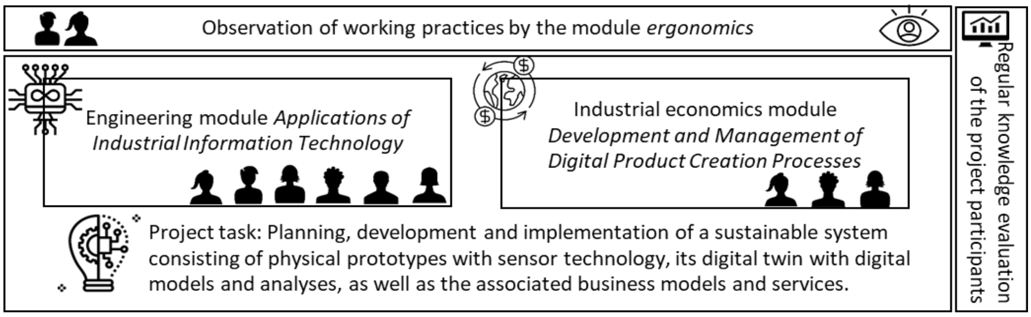

Figure 1: Composition of the modules for the PBL project at the IIT department

3.2 Continuous development of the teaching concept

As already mentioned, the project has been carried out not once but five times. In order to continuously improve the teaching concept and to gain real insights into the working methods of the project teams and

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the knowledge dynamics within the teams, the teams were observed by students of the Chair of Labour Studies during the course in 19/20 and 20/21. An ethnographic study design was used. This was evaluated and in turn was included in the further development of the project. (Mörike et al 2021).

In addition, teaching evaluations were conducted with the students over several semesters, in which, for example, their knowledge of sustainability, product development methods or interdisciplinary cooperation were repeatedly queried. Surveys were conducted at the beginning of the semester, in the middle of the semester and at the end of the semester and the results were compared. Furthermore, the students were asked to formulate lessons learned at the end of the project. These were then incorporated as far as possible in the coming semesters (see Figure 1).

3.3 Task definition and evaluation

The main task for the students was to design and develop sustainable products or systems, consisting of physical and digital elements, with a social and environmental relevant functionality. For the digital solution, the concept of DTs should be evaluated and specified to provide digital services.

All three perspectives of sustainability, i.e. economic, environmental and social, should be considered. In the context of an engineering degree, the economical and often also the environmental perspective are usually considered, while the social perspective is rarely included. In the semester project of the Department of Industrial Information Technology, the focus should therefore be particular on this perspective. For this purpose, we started a cooperation with the MatchMyMaker (MMM) project of the be.able association. There, impaired people with special problems that cannot be solved by conventional means can contact us. Solutions are then sought in hackathons. Some of the submitted problems, especially those with technologically more complex problems, are passed on to the IIT chair and their semester project, where they are being worked on by the students. This gives the students a real person with a real problem to solve. The social focus of the project is thus significantly increased and the motivation of the students is much higher, as they no longer have the feeling of only working for a university project, but of making a real contribution.

The entire course flow mirrored quasi-real industrial work processes and functions: the project teams were given a budget to procure the parts needed to produce a prototype, and two design reviews were conducted as examination performances. The lecturers acted as potential investors from industry to invest in producing the products on industrial scale. Here, the teams presented their ideas and had to defend their concepts in challenging discussions as if their team was competing for the investment.

In the semester 21/22, there were three case providers with three different challenges, each of which was solved by 1-3 groups.

1. *Handbike Challenge*: The aim was to develop a turning system for a handbike rider. If you want to drive onto the road with a handbike, it is usually very difficult to see the road because the bike is attached to the front of the wheelchair and you have a large distance to the front wheel of the bike. The rider, who has to sit, has no view of the road, especially if there are parked cars. This risk is to be reduced by a turning system.
2. *Philly Challenge*: Philly is a little girl (10 years old) who, due to a congenital disease, needs to be connected 24/7 to life support equipment (ventilation, feeding, etc.). The equipment needs to be powered by a power cable as a battery is too unsafe. To transport the equipment, an improvised trolley was built by her father on which everything can be placed. This can be moved around the flat with castors. However, the wheels constantly get caught on corners, making it difficult for Philly to move around. The task was to optimize the mobile transport and support system.
3. *The Drop Hand Challenge*: This challenge was submitted by Barbara, who has a disease that causes her to have fewer and fewer body muscles. For a while now, she has also had a drop hand (radial nerve paralysis), which means that she can still press her fingers down, but can no longer lift them. One of her greatest hobbies is to give small private piano concerts. Unfortunately, this is only possible to a very limited extent due to her drop hand, which is why she would like a solution, for example an orthosis, to help her play the piano better again.

The product concept and the final prototype were evaluated on the basis of environmental sustainability (use of sustainable materials) and economic sustainability (need for as little money as possible), the practicality of the product (presence of social sustainability) and the operational performance during the project (teamwork, distribution of working hours).

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3.4 Teaching staff and structure

The teaching staff for the project courses at the department has also evolved over the years. In order to teach the students true interdisciplinarity, the teaching tasks were also divided by domains. Subject-specific lectures were given by the professor or other experts from the department. These lectures are on classic topics of the product development process such as requirements management, change management, sustainability, collaboration in the development process or IT tools to support the development process.

There are also practical seminars that help the students with the implementation of the projects. External lecturers have also been engaged to explain, design thinking or the structure and methodical development of DTs, among other topics. If students or teams have individual questions, the lecturers offer consultation hours, which then provide specific support. In the design reviews, which count as an intermediate examination for the students, different experts from the subject area and industry are often present. Figure 2 gives an overview of the teaching staff and core elements of the seminar.

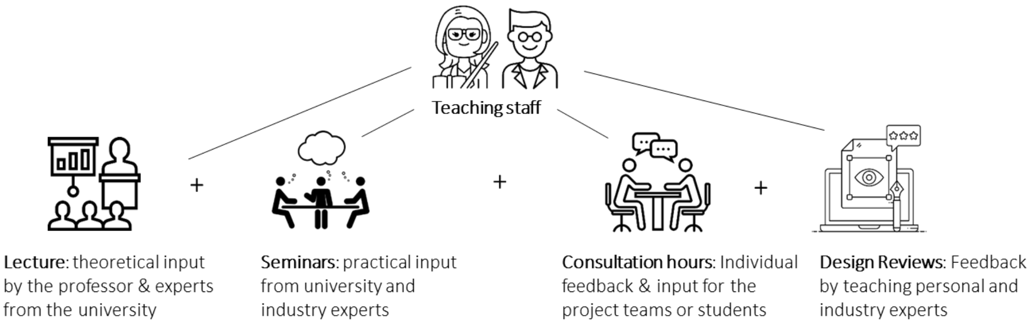

Figure 2: teaching staff and core elements

3.5 Methodological support for students to develop Digital Twins

The three use cases within the validation (see chapter 3.3) differed regarding the potential functions of the DT as well as the role of the physical system. While the use cases 1 and 2 had a pre-existing product, which was also to be adapted within the course (scenario B), the third use case is a parallel development of a product and its DT (Scenario A) (Riedelsheimer et al., 2021). The presented methodology contained the following development steps, which integrated three central DT schematics:

- DT scheme to define the general use case and scope (Riedelsheimer et al. 2020)
- Design Elements to describe the basic DT elements
- and 8D-model to describe the DT capabilities (Stark et al., 2019)

The central development steps of the method are depicted in Table 1. Within the case study, three main Design Reviews were conducted, and the methodology was only executed until the development of a first physical prototype with a limited data collection.

In general, a user centered development is suggested for the DT development – for human interfaces but also for IT-systems as main users. Within the case study the aspects of aggregated twins (e.g. fleet of products) as well as different variants of DTs were neglected.

Table 1: Overview of development steps and results within the case study

No	Step	Short description	Results
1	Existing product and boundaries	Analysis of the motivation to develop a DT and identification of the main problem that needs to be solved with the DT, boundary conditions, existing product in use (if applicable), as-is-process, and derivation of the first requirements.	First list of requirements, existing DT elements *Optional: LCA of existing product*
2	Concepts for DTs	Define different basic concepts from a user perspective to address the identified goal including personas for the main DT user, the DT user journey and respective business models.	Concepts: Personas, DT User Journey, Business Model Canvas
3	Service design	Definition of DT services in close cooperation with the business model and service design team to identify the first functional building blocks (FBBs).	Use case diagram, FBBs, functional model V1.0

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4	DT capabilities	Deriving of DT capabilities to refine the overall intelligence of the DT, its autonomy and automation level as well as prediction and simulation capabilities. Important for team and role planning.	8D-model, team and role specification
5	Requirements	Identification of functional and non-functional requirements as well as data and information need	Requirements list 2.0 (including data)
6	System design	Refinement of functional model, creation of a first solution neutral system model (e.g. component diagram)	Functional model V2.0, component diagram
7	System function structure	Integration of system perspective in the functional model	Integrated model of systems and functions
8	Sub functions	Detailing of functions to sub-functions	Model of subfunctions
9	Solution principles	Identification of technologically feasible solution principles as well as identification of their environmental impact	Overview of possible solution principles *Optional: LCA of solution principles*
10	Selection of solutions	Selection of solutions (e.g. with a morphological box) and documentation of the resulting system design	Solution specific component diagram
11	**Design Review I**	**Review of the developed concept with the respective functionalities and the proposed solution principles with the whole design team and lead**	**List of engineering and design changes**
12	Variant generation	Generation of several variants of the DT for different users in alignment with the different use cases and FBBs	DT variants *Optional: LCA of variants*
13	Virtual prototype product	Development of the physical product or its optimization and derivation of the bill of material (BOM), CAD-model, electrical plan drawings, …	Product models, BOM, Design elements
14	Virtual prototype DT	Development of software and IT-infrastructure elements, of the DT as well as data modelling and dashboard design. Here agile development methods should be applied (SCRUM)	BOM, data models, software architecture, sequence diagram, design elements
15	Make or Buy decision	Identification of parts and elements to be sourced or to be inhouse developed and produced	Order list *Optional: LCA of sourced parts*
16	**Design Review II**	**Review of the developed product, software and DT models (virtual prototype) with the whole design team and lead**	**List of engineering and design changes**
17	Physical prototype	Purchase process of physical parts, creation of a physical prototype of the (updated) physical product	Physical prototype of the product
18	Individual tests	Test of all components individually, e.g. dashboard, software modules	Individual test protocol
19	Partial integration	Interconnecting the sensors with the virtual prototype to test the interconnection with test data	Integration test protocol
20	**Design Review III**	**Review of the whole system with the team and the core user**	**List of engineering and design changes**

Within the case study, the last design review was conducted after the partial integration testing. The next steps of the development process, that are not depicted in the case study, usually are:

- Integration test of all elements of the DT, product, software as well as the productive systems in the usage environment to verify the requirements fulfilment.
- User studies to validate, if the user needs are actually fulfilled in terms of functionality and usability and added value of the services.

The main tasks of the DT within the case study were defined to be within its function as communication, control and monitoring element. It should be used to foster the monitoring and optimization of the environmental impact within the developed overall system.

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3.6 Project results

The project results were all developed fully in a digital working environment and all seminars and the Design Reviews were conducted virtually. Only the presentation of the overall results at the end of the case study was executed in a hybrid mode with a core team presenting the physical prototype, data collection and DT interconnection onsite. All six groups were able to build a functioning prototype. In total, three groups worked on the Handbike Challenge, two groups on the Philly Challenge and one group on the Drop Hand Challenge. The following three illustrations show exemplarily the virtual prototypes that were created.

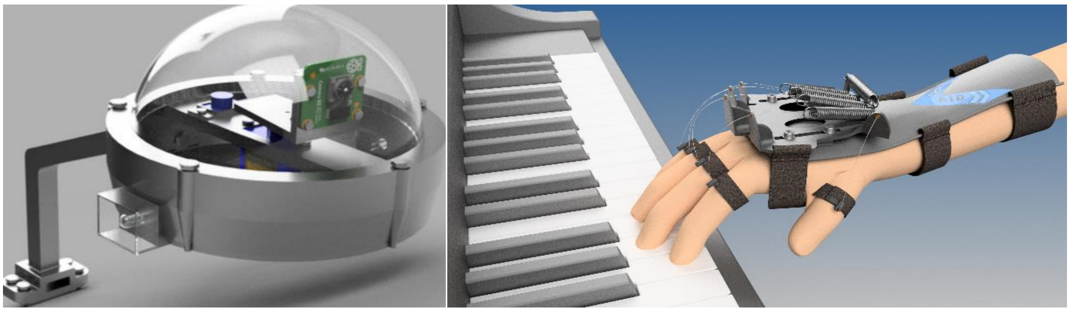

Figure 3: Camera system for the handbike to safely assess the traffic situation and orthosis for the drop hand

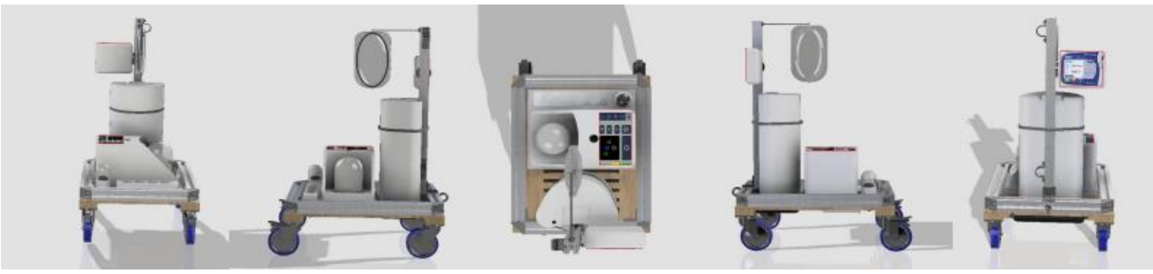

Figure 4: CAD models of medical supply cart for Philly

All project groups achieved the given task of developing a system consisting of a physical product oriented to fulfil the customer needs as well as a DT, the data collection and respective services. The level of detail and complexity of the solutions differed slightly, but all project teams fulfilled the main requirements. All prototypes stayed within the budget of 100€ and were largely built from waste (at least 50%). Due to the close cooperation with the use case providers of MMM, the social relevance was put in focus. At the same time, environmental aspects were considered, e.g. by energy monitoring within the DT. The role of the DT in all projects was mainly a digital supporting system for monitoring and optimizing the individual instance (see Figure 5).

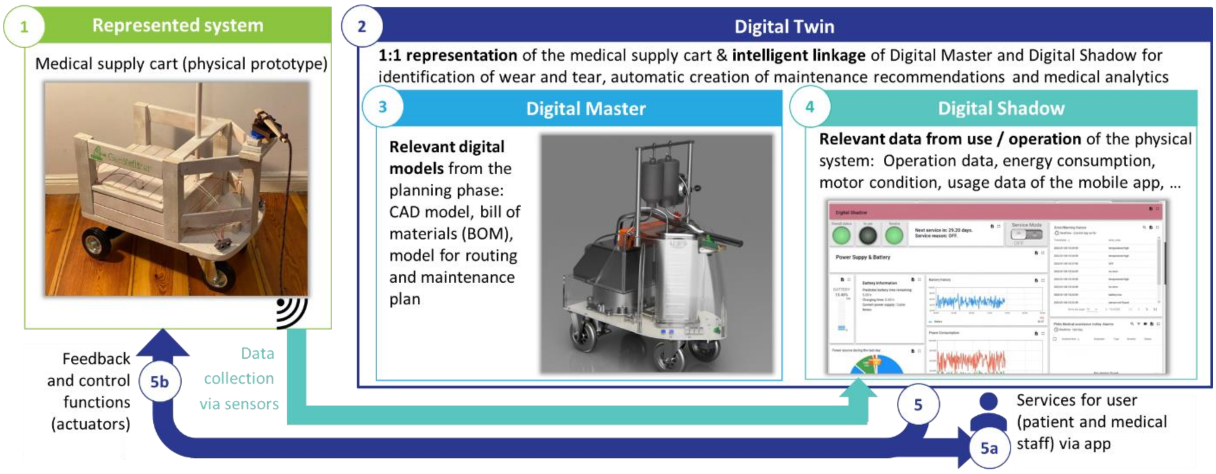

Figure 5: Digital Twin result for Philly challenge

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The represented system (No. 1) is predefined by the main users requirements. The Digital Twin (No. 2) comprises the Digital Master data (No. 3) and Digital Shadow (No.4) and provides DT services (No. 5). In the depicted case, it provides instance specific feedback to the medical staff (5a) and maintenance & routing optimization (5b).

4 ANALYSIS OF THE TEACHING CONCEPT AND APPLIED METHOD

To analyse the teaching concept as well as the applied method, three surveys were conducted in total:

- Survey I – before the first seminar with n = 56 participants
- Survey II – after DR I with n = 48 participants
- Survey III – after the end of the project with n = 49 participants.

In the following, an overview of the most relevant results will be given. In the first part of the study the students were asked about their basic knowledge. Overall, the majority of the case study participants had experience with the role executed within the project (80%), 25% even with industrial application. With regard to the experience with development projects the survey showed that 18% have applied methodical development methods before and 27% at least partly. For 18%, on the other hand, the application of a development method was totally new. Most known was the V-model (14%) or the classical methodical design as described within the VDI 2221 (13%). And, for experience with DTs 34 percent have knowledge about DTs and 66 percent have no knowledge about DTs. These results indicate, that there is a relevant number of experienced participants, but the majority is inexperienced. Therefore, the teaching approach plays an integral role in fostering the knowledge and enabling the participants to develop complex systems of products and DTs.

After first design review, more than 83% felt confident with their knowledge and application level of DTs. This showed an increase from 15% already during the conceptual phase, which amounts to 43% of the participants with a learning effect. With regard to the applied method, 66% of all participants said that they followed the proposed methodology in the exact order of the process steps. For 20%, there is a potential to improve the applied method with regard to the chase study. The identified improvement potential was with regard to the need for agile aspects to give credit to a faster development process and speed as well as the integration of more domain specific working early on. The survey also showed that DTs do not always have a right to exist. They need a clear objective and user behind it. There is a high skill level and set of competences in the area of software development, mechanical engineering, but also business model development necessary to develop DTs. Also, the relevance of the developed models and diagrams was analyzed. The technological analysis of the chosen solution principles, the functional model and the system structure were stated as the easiest to apply and most relevant diagrams for the development objective. The clearest added value was seen in the creation of a virtual (CAD-model and dashboard mockup) and physical prototype as well as the BOM, which might be due to the high relevance of the product development process itself.

Within the final survey, the applied method was validated. The application of a user centered approach was seen as very suited (for more than 65%). More than 50% of the participants stated, that they would use the method in future development of sustainable DTs and 43 % for general DT projects. The biggest challenge lies within the integration of sustainability within the DT task (39%).

The relevant limitations to be noted are with regard to the group of case study participants, who were partly inexperienced. Also, there was an inconsistent number of participants over the three surveys. Especially the working remote and from home due to COVID-19 restrictions and the restricted time of 5 months for development project brought some additional challenges to the case study that should be considered within the analysis. One drawback for the DT relevance was, that not all social challenges as provided by MMM brought an integral need for DT services with it. This created a perceived situation of two customers for the students.

The analysis also revealed more general feedback, which showed a diverse spectrum of fulfilled expectations and ultimately motivation of the students, which influence results and success of the learning method and task.

5 CONCLUSION AND OUTLOOK

At the Department of Industrial Information Technology, several teaching projects are conducted in PBL format. All of them have a different focus (e.g. MBSE, integrative development, interdisciplinary

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development, virtual engineering, industrial design and others). However, it can be said that the presented PBL course is one of the most complex modules in the subject area. As shown in, there are five main points that are identified as success factors of the seminar:

1. First, the complexity of task given, such as the development of a DT with a virtual and physical prototype for very unique requirements of a real case.
2. Also, the interactive learning with. In addition to the thematic weekly lectures and, weekly tests are conducted. This avoids a big test and so-called "bulimic learning".
3. Additionally, the subject-specific seminars and the input from experts.
4. Also, the interdisciplinary learning through the combination of two modules.
5. And lastly, the social and environmental consideration by the cooperation with MMM and the applied research institute. Sustainability plays a major role here in all points.

In the feedback discussions, students mentioned again and again how great and unique they experienced the cooperation with MMM and that it created a much higher team motivation. Basically, it can be said that the seminar has grown over the years into a unique combination of teaching and learning content, which is a good reflection of the future challenges for engineers. The feedback and the deeper analysis showed that the overall learning objectives were fulfilled: design thinking, DT development and sustainable engineering as well as interdisciplinary collaboration.

The learnings, however, had some limitations due to the design of the course. The cooperation with MMM is a great enrichment for the students, but it also brings them into a conflict as to which requirements they have to fulfil as a priority. This point should be worked on further, but it should also be remembered that the aim of the seminar is to create conditions that are close to industry, and even in industry, students will receive requirements from several sides and then have to make decisions. Another influencing factor that should not be neglected is the high effort for and autobiography of the teaching staff. Of course, this always depends on motivation and commitment. For the semester project of the IIT department, several experts could be made available. Not only experts from the university, but also from industry. Here, of course, special commitment is required. In some cases, a win-win situation can arise, for example by conducting studies with the students. However, this is not always possible.

In order to get a more comprehensive picture, the students in the study might have to be interviewed again, for example, one year after graduation. This would allow us to see to what extent the students can apply what they learned in the seminar in their current work environment. Due to the university environment, an industrial case study should be conducted to fully validate the applied method with a realistic set of test data and a collaboration environment.

Basically, the PBL approach was able to set up a complex seminar that gives students a very realistic insight into the future world of work and encourages them to develop in this way.

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