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A RETROSPECTIVE STUDY OF THE BENEFITS OF THE "CPS ENGINEERING" COURSES FOR CURRENT GRADUATE CAREERS

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Abstract. Well-trained engineers are needed to plan, design, develop and maintain cyber physical systems (CPS) that form the core of modern digitized industrial infrastructures. The development of such systems is challenging, however, according to industry representatives, the graduates are not adequately prepared for professional practice. In particular, there is a lack of transferable skills. To be employable and successful in their careers, students must have the opportunity to gain experience developing such systems during their studies and practice both technical and transferable skills in realistic environments. This paper aims to provide a retrospective view of the outcomes of two courses in industrial CPS engineering within the master's program at ITMO University, St. Petersburg, Russia, conducted in the winter semesters of 2016/17 and 2017/18. For this purpose, graduates who participated in these courses were interviewed in 2022. The respondents reflected on the benefits of these courses for their work. The graduates reported that participation was highly relevant to both their professional and personal development. They indicated that they especially valued programming skills and collaboration and communication skills that they acquired in the courses.

Keywords: *industrial cyber physical systems, education, T-CHAT educational approach, qualitative study*

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ПРЕИМУЩЕСТВА КУРСОВ ПО СОЗДАНИЮ КИБЕРФИЗИЧЕСКИХ СИСТЕМ ДЛЯ ТЕКУЩЕЙ КАРЬЕРЫ ВЫПУСКНИКОВ: РЕТРОСПЕКТИВНОЕ ИССЛЕДОВАНИЕ

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Аннотация. Для планирования, проектирования, разработки и обслуживания киберфизических систем, которые составляют основу современных цифровых промышленных инфраструктур, необходимы хорошо обученные инженеры. Разработка таких систем является сложной задачей, однако, по словам представителей отрасли, выпускники недостаточно подготовлены к профессиональной работе, в частности, не хватает практических навыков. Для последующего трудоустройства и успешной карьеры студенты должны иметь возможность получить опыт по созданию таких систем во время учебы и отработать как технические, так и практические навыки в реальных условиях. В статье представлен ретроспективный обзор результатов на примере двух курсов по проектированию промышленных киберфизических систем в рамках магистерской программы Университета ИТМО, Санкт-Петербург, Россия, проведенных в зимних семестрах 2016/17 и 2017/18 гг. С этой целью в 2022 г. были опрошены выпускники, прошедшие эти курсы, им предлагалось оценить пользу курсов для своей работы. По словам выпускников, участие в этих курсах имело большое значение как для их профессионального, так и личного развития; также они отметили, что особенно ценят приобретенные на курсах навыки программирования и совместной работы.

Ключевые слова: промышленные киберфизические системы, образование, целостный образовательный подход T-CHAT, качественное исследование

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Introduction. Cyber Physical Systems (CPS) consist of components that have a physical and a virtual part. Physical parts are real physical objects such as sensors, actuators and machine tools or combinations of them. The virtual part is the software that serves as a cyber image of the physical objects. In combination with Internet of Things, CPS build up the core elements of Industry 4.0 concept [1], and of the Industrial Cyber Physical Systems (ICPS) [2] — the core of real-world digitalized and networked industrial infrastructures.

Well-trained engineers from various disciplines are needed for the planning, construction, operation and maintenance of such industrial infrastructures. Due to the interdisciplinary nature of ICPS engineering, sound technical skills are not enough [3—5]. As interdisciplinary teams develop ICPS, technical skills combined with strong transferable skills, which include, e.g. skills in effective communication and collaboration, problem-solving, innovation and the ability to engage in lifelong learning are required to work effectively and efficiently. In addition, technical skills from various fields such as electrical engineering, mechanical engineering, computer science, networking, analytics, and physics are required.

The ICPS engineering is a new discipline and there is a lack of professional ICPS engineers in the industry. These engineers, in turn, often lack the technical and transferable skills expected by industry [3, 6]. Two main issues have been found by review of the literature on ICPS engineering education [2, 3]: 1) social competences and attitudes are not sufficiently addressed by CPS curricula and courses, and 2) the methodology used in CPS curricula and courses is restricted.

The task-centric holistic agile teaching approach T-CHAT [7, 8] is developed to address these issues. It proposes a combination of pedagogical approaches and teaching methods to improve both the technical and transferable skills of students. The T-CHAT combines five pedagogical approaches 1) perceptional learning, 2) project-based learning (PjBL), 3) problem-based learning (PBL), 4) research-based learning (RBL), and 5) face-to-face teaching (F2F).

The T-CHAT approach was originally developed to teach ICPS engineering in joint courses at ITMO University, St. Petersburg, Russia, and University of Applied Sciences Emden/Leer, Germany [9]. These courses, which addressed aspects of real-life ICPS projects and were thematically linked, took place in the winter semesters 2016/2017 and 2017/2018. The main goal of these courses was that students sustainably attain the technical knowledge and soft skills to use in their future profession. In 2022, 4 to 5 years after these courses, we aim to explore the following research question:

RQ How do graduates perceive the benefits of taking courses taught using to the T-CHAT educational approach to their current careers?

Background. The ICSP engineering is an interdisciplinary discipline that requires interdisciplinary practice-based education. In interdisciplinary learning, “learners integrate information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines to craft products, explain phenomena, or solve problems, in ways that would have been unlikely through single-disciplinary means” [10]. Therefore, the use of teaching methods that support interdisciplinary learning is a natural choice for teaching ICPS engineering.

Master’s Program “Industrial CPS”. Master’s program “Industrial CPS” at ITMO University served as a container for two joint “ICPS engineering” courses (for details of the program see [11]). This program offers an integrated set of basic and optional courses to teach ICPS/Industry 4.0 concepts and to create the basis for independent student research. The outcomes of this program cover three main areas: 1) personal competencies, 2) soft skills, and 3) basic professional skills.

Students who attend this program and courses have heterogeneous professional backgrounds. This heterogeneity must be taken into account in the classroom. The teachers’ task is to consolidate students in a learning community and give them the responsibility for learning.

To achieve the educational goals, new innovative teaching concepts are required that focus on the teaching of both technical and transferable skills. The T-CHAT educational approach addresses the development of the required skills.

T-CHAT Educational Approach. The T-CHAT educational approach combines five pedagogical approaches to support the development of students' technical and transferable skills in the T-CHAT learning process [7]. In this learning process, students are first given an intuitive understanding of the subject matter by giving discipline-typical examples, tasks, and observations from everyday life (for perceptional learning approach see [12]). This intuitive understanding is further conceptualized by means of induction into theoretical knowledge. The conceptualization may be reached, for example, by presentations held by teacher during lectures or by PBL activities during labs. The perceptional learning approach is to be used intensively for the threshold concepts of the subject matter, i.e. for the topics in the material that have a central conceptual role and in which a large number of students often have difficulties.

F2F-teaching is conducted to teach main concepts and ideas. In order to achieve a trusting atmosphere in the lectures, it is recommended to encourage the active participation of students and to involve them in discussions. Activation of students can be achieved through mixing short conceptual and theoretical presentations with the phases of individual and group work. For example, students can solve a short 5-minute task and the results are immediately discussed in the plenum.

It is important to find out at the end of each lecture, which topics students have understood, and which topics remained unclear. This can be done by short anonymous feedback in paper form or electronically. The correctness of the students' answers can be checked e.g. by control multiple-choice questions on the material taught in the lecture. Student feedback is used to flexibly adapt the learning process to the students' understanding and progress. The open points raised by the students are discussed at the beginning of the next lecture.

During labs, the PBL approach can be applied by giving students problems as individual or group tasks. It is recommended to set the tasks so that they are started during the labs and completed as homework individually or in groups.

It is recommended to start with PjBL after students have acquired some background knowledge and skills in the subject matter. To avoid free riders and social conflicts during the project work, small groups of maximum four persons are recommended. Students can organize their groups themselves. Some instructions may be needed before starting work.

Appropriate tasks can be set on the use of RBL. These tasks may be on topics whose mastery is fundamental for a deep understanding of the topic and which are so complex that some research is required.

Experiment. "CPS Engineering" Courses. Two "ICPS engineering" courses were implemented using the T−CHAT educational approach. German students studying computer science and Russian students studying instrumentation and control engineering took part in these courses, which were supervised by German and Russian tutors.

The learning outcomes of two joint "ICPS engineering" courses were similar to the intended outcomes specified in the Master's program "Industrial CPS" at ITMO University (for details of the program see [11]).

In the first course, the students needed to design, develop and validate a CPS that emulates a small factory with several robots transporting building blocks from a source palette to a goal palette while cleaning and painting them (for details see [8]). Solving this task was carried out as a project running in an environment, in which the tutors functioned as customers ordering a CPS from a "manufacturer", in this case the students. The students were responsible for setting up a technical infrastructure for CPS development, project management and communication, forming project teams, and organizing the project work. The course was planned and implemented using the methodology of T-CHAT [8].The main objectives were to facilitate effective communication and collaboration, as they are crucial for the project success in technology-intensive projects within in globally distributed developments [13].

In the second course, the scenario of the first course was extended to include ERP and procurement requirements. The structure of the two courses was similar and is shown in Fig.1.

Theme/Method \ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Opening workshop															
Distributed Software development															
Closing workshop															
Perceptional teaching															
Face-2-Face teaching															
Project based teaching															
Problem based teaching															
Research oriented teaching															

Fig. 1

Interviews with Graduates. A qualitative study was conducted to answer the research question. Structured interviews were carried out with six volunteer graduates of ITMO University who had participated in the "CPS engineering" courses (for questions see Appendix Structured interviews with students). First, personal information such as degree obtained, and work experience was collected. Then, interviewees were asked to look back at the courses they had attended in 2016/17 and 2017/18 from two perspectives: 1) back in 2016-2018 and 2) now, after they had gained some work experience. The interview questions aimed to explore how the graduates perceived the development of their professional, personal and soft skills. Fig. 2 schematically illustrates the intention and structure of the interviews.

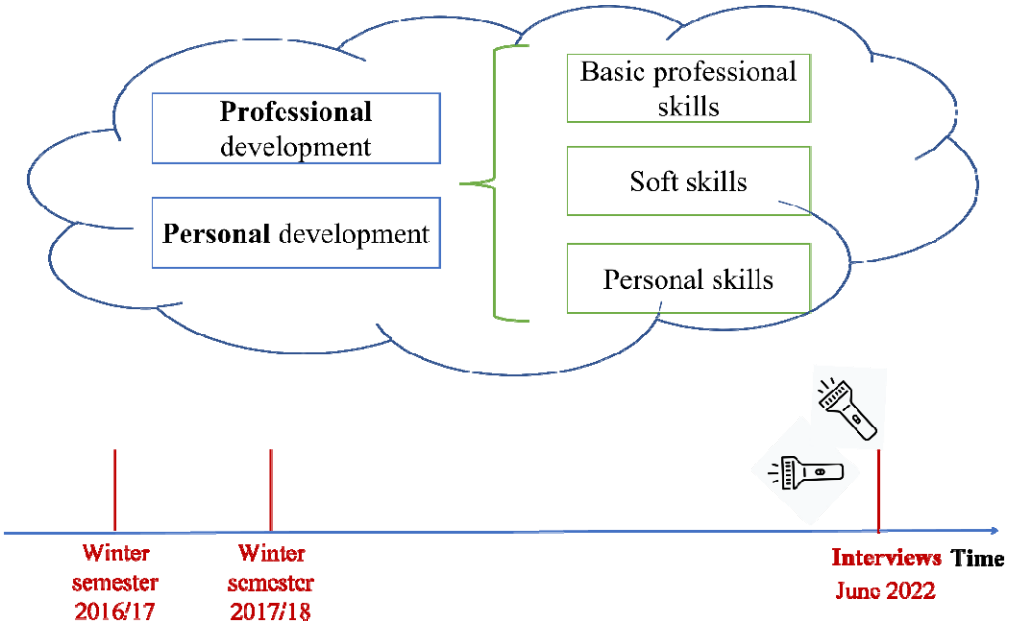

Fig. 2

The interviews were recorded, transcribed, and coded. The categories and themes were identified mainly based on the structure of the interviews. Based on these categories and topics, the responses were analysed to examine the perceptions of the students participating in the course about the usefulness of this course for their professional and personal development, thus answering the research question. Based on this analysis, qualitative explanations and generalizations were developed that remain close to concrete data and contexts, but go beyond simple summary descriptions of the data [14].

Results. All six interviewees were male graduates of ITMO University's "Computer science and engineering" program. Table 1 shows the graduates' data on their degrees and work experience in the profession. One interviewee did not work in his profession after graduation.

Table 1

Interviewee	Degree	Work experience in the profession
Interviewee 1 (I1)	Master	2.5 years
Interviewee 2 (I2)	Master	1 year
Interviewee 3 (I3)	Bachelor (in 2017)	5 years
Interviewee 4 (I4)	Master (in 2019)	No experience
Interviewee 5 (I5)	Bachelor (2017)	7 years
Interviewee 6 (I6)	Master	3 years

Two categories and four associated themes were identified for each category based on the structure of the interview questions (see Fig. 3) and are used as a framework for summarizing students' perceptions.

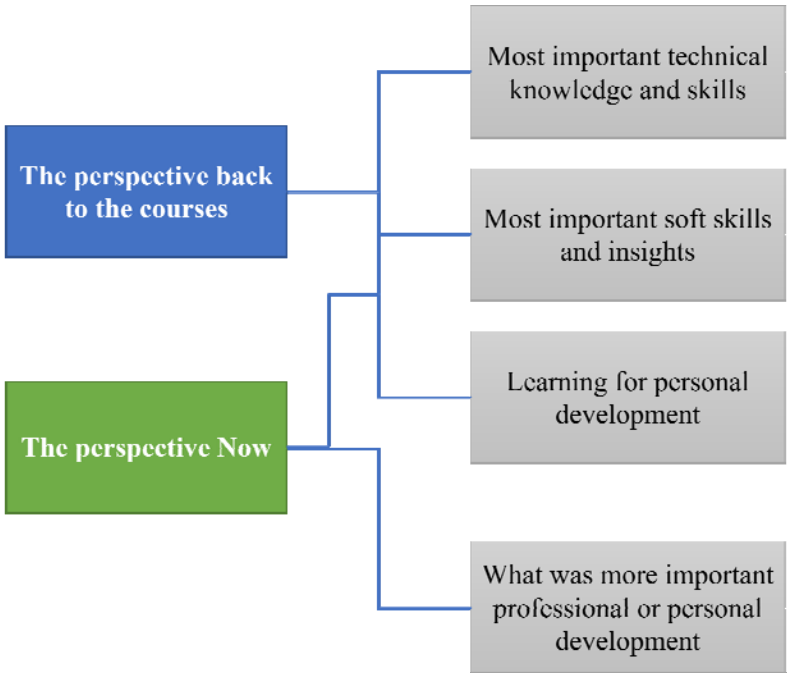

Fig. 3

Table 2 lists the identified codes within both categories "Back to the course" and "Now" and maps them to the interviewees.

Table 2

Theme	Categories			
	The perspective back to the courses		The perspective Now	
	Codes	Interviewee	Codes	Interviewee
Most important technical knowledge and skills	The use of various programming environments and tools	I1, I2, I3	The use of various programming tools and libraries	I1, I2
	Learning new programming languages. Programming skills	I2, I6	Programming skills	I6
			The ability to understand technical documentation	I2
	Algorithms, data structures, databases	I3, I5	Basic knowledge of network and internet applications	I4
	Technology for parts processing	I3	Technological skills	I6
			Industrial plants	I6

Continuation of Table 2

Theme	Categories			
	The perspective back to the courses		The perspective Now	
	Codes	Interviewee	Codes	Interviewee
Most important soft skills and insights	Teamwork	I1, I2, I4, I5, I6	Teamwork	I1, I2, I4
	Negotiating in team, finding a consensus, and searching for compromises	I2, I4	Negotiating as a team to reach a common consensus and a suitable solution. Finding compromises	I1, I2
	Communication	I3	Professional and constructive communication in team	I1, I6
	Project management and work coordination	I5, I6	Methodology for project management (SCRUM)	I5
	Presentation of project results	I6	Presentation and writing reports	I6
	Leadership	I5		
	English language	I6	English language	I6
	The ability and courage to express my disagreement with the other team members	I1		
	The ability to analyze information	I2	Analytical skills	I2
			Courage and curiosity to learn new things	I1
Learning for personal development	I identified the gaps in my technical skills	I1	The ability to express my disagreements with team solutions	I1
	I realized that I love teamwork and want to be a leader	I1		
	Communication with people of different age, from different professional backgrounds	I2, I6	Communication skills	I2
	The ability to actively listen to people	I5	Ability to achieve goals within a given time frame	I5
	Self-confidence	I6	A view on how other people learn and work, participate in project work. It was useful to understand that other people work differently	I6
What was more important — professional or personal development	Skills for my professional development were more important			I1, I2, I5
	Skills for both professional and personal development were important			I3, I4
	Skills for my personal development are more important, particularly self-confidence and confidence in my ability to work in projects			I6

The graduated students interviewed can recall the benefits with varying degrees of accuracy 4 to 6 years after taking the course. Two interviewees, I3 and I4, can barely recall the knowledge and skills they had acquired in the course. In particular, respondent I4 who did not work in his profession could not recall the course details. However, the remaining respondents described their experiences in detail and reflected on the benefits they derived both professionally and personally.

Half of the interviewees believed that skills they acquired were most important for their professional development, two respondents mentioned that skills were important for both professional and personal development, and only one respondent emphasized that skills he acquired for his personal development predominated.

Comparing the two different perspectives — “back to the course” and “now” — there are only insignificant differences in the responses of each graduate. Most of them cited almost the same benefits for both perspectives. However, some interviewees were a bit more thoughtful. Respondent I6,

for example, stated that he only perceived the benefits of the course much more deeply after he had started his professional work. It was only then that he realized the importance of the experiences he gained during the course, namely project experience and leadership skills, the insight that people work and learn differently, and the self-confidence gained. He uses the insights in his work as a team leader. I1 mentioned that during the course he recognized some gaps in his technical skills and that he worked a lot to fill those gaps after the course. I1 and I2 emphasized that they learned to negotiate as a team to find consensus and the best solution.

Regarding technical knowledge and skills, most interviewees cited the acquisition of programming skills and the use of various programming environments and tools as the most important then and now for their careers.

It is worth noting that the ability to work in team was mentioned as the most frequently acquired soft skill, followed by professional communication skills and negotiation ability. Some respondents cited analytical skills, courage and curiosity to learn new things, and leadership qualities as benefits of attending the course.

Conclusion. This paper retrospectively examines the benefits that university graduates have derived from them participation in "ICPS Engineering" courses for their post-graduation careers and work experience. These courses were taught using the T-CHAT holistic educational approach and addressed the development of both technical and transferable skills.

The analysis of qualitative data collected through structured interviews revealed that the graduates primarily use the technical skills in programming and programming tools and environments, and transferable skills such as collaboration and communication, especially negotiation strategies and team consensus building, acquired in these courses in their current careers. Some graduates also indicated that they valued analytical thinking skills and the acquired ability to independent learning of new topics. The graduates also reported benefits for their personal development, such as increased self-confidence. These results demonstrate the positive long-term effect of the learning experiences students have had in the courses taught using the T-CHAT educational approach.

APPENDIX. STRUCTURED INTERVIEWS WITH STUDENTS.

Some personal questions:

— What degree do you have?

— How long is your work experience in your profession after graduation?

If you look back at the module you completed, from the point of view of THEN:

1. From a professional point of view:
   a. What technical knowledge and skills did you acquire? What was new for you? What was most important?
   b. What soft skills did you acquire? What insights did you gain?
2. What skills did you learn back then for your personal development at that time?

If you look back at the module you completed, from TODAY'S point of view:

1. From a professional point of view:
   a. What technical knowledge and skills you acquired back then do you value most today or is most useful for you today?
   b. What soft skills you acquired back then do you value most in your current professional work? What insights have been most important for your professional work?
2. What skills you acquired back then have been most important for your personal development?
3. What has been for you more important: knowledge and skills that you acquired for your professional development or for your personal development?

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